

High resolution simulation of Stockholm's air temperature and its interactions with urban development

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ABSTRACT

Stockholm is expanding fast in response to increasing housing needs. This paper evaluates the consequences of land-use changes on summer temperatures. Urban development scenarios for 2030 and 2050 were developed together with the municipality. The spatial and temporal variations of the changes in the urban air temperature are simulated at 1 km grid resolution applying a dynamical downscaling technique. The comparison against observations obtained during 5 years at 11 weather stations shows that the high resolution model captures the dynamics of the intra-urban air temperature gradients with good performance skills. Scenario results indicate that the temperature of summer 2014 would increase over the new built-up areas by, on average, 0.29 °C in 2030 and 0.46 °C in 2050, up to a local maximum of 1.35 °C in the latter, as a consequence of urbanization. The number of days with temperature above the 75th percentile for the summer months increases by up to 10, with locations closer to the sea being less prone to temperature maxima. The spatial coverage of this warming effect is predominantly local, occurring mostly over the transformed/densified area. Better knowledge on how urban temperatures are affected by on-going urbanization is needed also in high latitude cities.

1. Introduction

Heat waves are projected to increase in frequency, intensity and length due to climate change (IPCC, 2014), with higher risks for heat-related morbidity and mortality, particularly in urban areas because of the urban heat island (UHI) effect (Hoegh-Guldberg et al., 2018). In addition, this cumulative impact on the heat stress of dwellers can be aggravated by the potential intensification of UHIs during heat waves (Li and Bou-Zeid, 2013).

The impact varies over regions and populations depending on acclimatisation, adaptation measures and variations in susceptibility (Gasparrini et al., 2015). Especially in areas where the local populations were not prepared to cope with heat, the temperature-mortality relationship may have been modified by higher urban temperatures reported in the last decades. This may explain the increase in the health effect of high temperatures observed in the northern cities of Helsinki and Stockholm (De' Donato et al., 2015). In the Stockholm region, an additional 10–20% of deaths on average have already been attributed to more frequent heat episodes (Åström et al., 2013).

Climate studies predict an increase in temperature in Scandinavia larger than the global average (Vautard et al., 2014), with a warming across Sweden ranging from 2 to 4 °C under an increase of 2 °C in global mean surface temperature compared to the pre-industrial period (Hoegh-Guldberg et al., 2018). Furthermore, it is expected that a warmer climate will augment the likelihood of

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heat waves, in the example of the summer of 2018 in Sweden, emphasized by the low awareness of the negative health effects of heat in this region (Åström et al., 2013). Altogether, these facts bring special attention to how high latitude cities will adapt to the risks associated to climate change and urban growth, in particular regarding heat stress.

Previous research has quantified the UHI in different locations in Sweden, namely in the larger cities of Stockholm (Gustavsson et al., 2001), Gothenburg (Eliasson and Svensson, 2003) and Malmö (Bärring et al., 1985). Although it is common to associate a given city with a spatially averaged UHI intensity, the intra-city variation of building density and materials, the presence of green and blue infrastructure and the anthropogenic activity generate local climates within the city (Arnfield, 2003; Grimmond et al., 2010; Mills et al., 2010). To be able to accurately simulate the fluxes between the complex urban physiography and the atmosphere, meteorological and climate models are gradually shifting into convection-permitting scales. As recognized in the latest IPCC's Special Report (Hoegh-Guldberg et al., 2018), an “appropriate method of downscaling is crucially important” in the assessment of local impacts of climate change at a scale that is directly affecting humans and ecosystems. This is particularly relevant given the widespread policy of urban densification aiming at the compact city (Skovbro, 2002).

In line with this tendency, Stockholm in Sweden has been following a strong urbanization trend with an average demographic growth of more than 15,000 inhabitants/year over the past decade, and standing as one of the fastest-growing regions in Europe (City of Stockholm, 2018). Current development plans reveal a city that is expanding mainly by constructing on areas presently occupied by nature. To the knowledge of the authors, the loss of the vegetation-induced cooling of ambient air (Saaroni et al., 2018; Samson et al., 2019) has, however, not yet been quantified in Stockholm.

In this context, this work analyses by means of high resolution dynamical downscaling how the urban/regional development planned for Stockholm will affect the spatial variation of the city's air temperature during a warm summer period. In particular, we (i) quantify the intensity of the warming potentially induced by the city expansion and densification, and (ii) investigate the spatial extension (local vs widespread) of this effect.

2. Method

The sensitivity of weather conditions, with a focus on air temperature, to surface changes was evaluated using a dynamical downscaling technique (described in Sections 2.1 and 2.2). This method provides an improved representation of the complex physical and dynamical processes occurring in the urban atmosphere when compared to larger-scale models or statistical methods historically used for studying the urban climate.

Two development scenarios were defined for this purpose, representing Stockholm in the years of 2030 and 2050 (Section 2.3). Meteorological forcing corresponding to the summer of 2014 was used in both scenarios, which gives an indication of how the city's climate would have responded to this hot summer conditions if the development plans were fully implemented at that time.

2.1. Dynamical downscaling

The flowchart in Fig. 1 provides a generic description of the dynamical downscaling process. In the core of this method is the numerical weather prediction (NWP) system HARMONIE-AROME (Bengtsson et al., 2017). As main inputs, the model relies on a refined high-resolution physiography database, lateral boundary data provided by reanalysis, and surface observations. In the next step the initial states for the atmospheric and surface model are generated, where the previous 6-hour forecast serves as a first guess. Finally, a 12-hour forecast of the meteorological state is produced, describing pressure, wind, temperature, humidity, clouds and precipitation. This data is post-processed for the calculation of a set of selected Essential Climate Variables (ECVs) and indicators. This method was previously validated in Gidhagen et al. (2020).

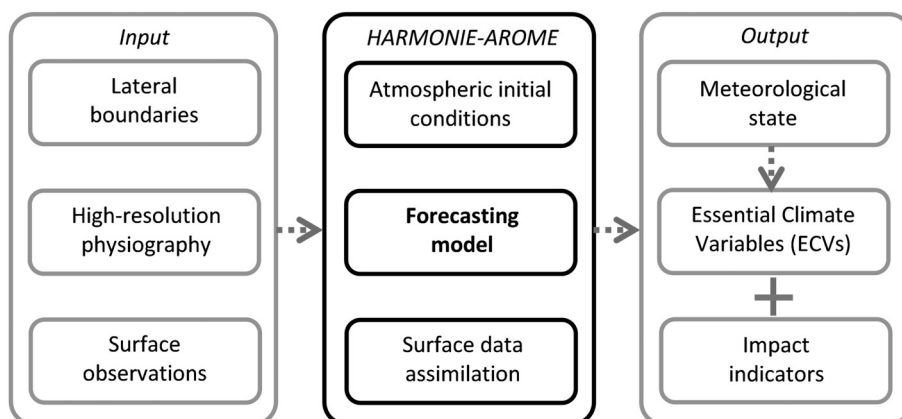


Fig. 1. Simplified flowchart of the dynamical downscaling process with HARMONIE-AROME.

2.1.1. Forecasting model

The dynamical downscaling is carried out with cycle 40h1.1 of the NWP system HARMONIE-AROME (Bengtsson et al., 2017). This model is used operationally within the HIRLAM consortium, e.g. in the MetCoOp collaboration (Müller et al., 2017), currently between Sweden, Norway, Finland and Estonia, and is part of the shared ALADIN-HIRLAM system, developed by the 26 countries of both NWP consortia. HARMONIE-AROME has been used for operational weather forecast in Sweden since 2014. As a difference to the operational setup, the version employed here uses a higher horizontal resolution with a 1-km grid size, although with a cubic grid instead of linear, and without upper air data assimilation (for more details see Gidhagen et al., 2020).

HARMONIE-AROME is a spectral limited area model aimed for the convection-permitting scales that has been developed for using the full non-hydrostatic equations, since the vertical velocity is large at the resolved scales due to convection and orographic forcing. The physical parameterizations (of radiation, thermodynamic adjustment, cloud-cover, cloud-microphysics, turbulence and shallow convection) are based on AROME, as described in Seity et al. (2011). Specific changes in HARMONIE-AROME were developed within the HIRLAM consortium and are described in Bengtsson et al. (2017).

2.1.2. Surface model

Urban morphology, surface materials, vegetation characteristics and human activity are key drivers of the urban climate, being capable of generating strong intra-city spatial gradients of (air and mean radiant) temperature or wind. In the version of HARMONIE-AROME applied here, surface/atmosphere interactions are computed by version 7.3 of the model SURFEX (Masson et al., 2013), with the setup specified in Bengtsson et al. (2017).

For the description of the surface, SURFEX uses a tile approach that allows accounting for sub-grid heterogeneity, which means that meteorological parameters are provided by the model for each tile fraction within a grid cell, in addition to the weighted average of that specific parameter. Four tiles can be defined according to the following classification: ‘Town’, ‘Nature’, ‘Lake’ (inland waters, including lakes and rivers) and ‘Sea’ (for both seas and oceans). The ‘Town’ tile can be composed of buildings, roads (or other paved surfaces) and green areas. Vegetation in the ‘Nature’ tile can be formed by a combination of 12 possible patches (bare soil and rocks, permanent snow, marshes, 2 types of grassland, 3 types of forest and 3 types of agricultural landscapes), while in the case of urban green these 12 categories are aggregated into bare soil and 2 types of vegetation (low and high).

The surface land-cover physiography is specified by a modified version of ECOCLIMAP-II (Faroux et al., 2013), as detailed in Section 2.2.6. Topography was created based on the Global Multi-resolution Terrain Elevation Data (GMTED2010) (Danielson and Gesch, 2011), while clay and sand fractions are based on FAO (2006).

Depending on the type of surface, different modelling schemes are activated in SURFEX: the Town Energy Balance (TEB) model (Masson et al., 2013) over urban areas; the Interaction Soil-Biosphere-Atmosphere (ISBA) scheme with a force-restore approach (Boone et al., 1999) on soil and vegetation; the FLake model (Le Moigne et al., 2016) for lakes and coastal waters; and the Exchange Coefficients from Unified Multicampaign Estimates (ECUME) scheme (Belamari, 2005) for describing sea/ocean fluxes. Stockholm's city physiography (see Fig. 2) is particularly complex due to the number of islands and lakes, and the proximity to the sea, requiring full use of the above-mentioned surface models.

TEB (Masson, 2000; Masson et al., 2013) is responsible for simulating the major physical processes occurring in the urban environment. This ‘building-averaged’ model follows the canyon approach, splitting the urban energy budget into three different

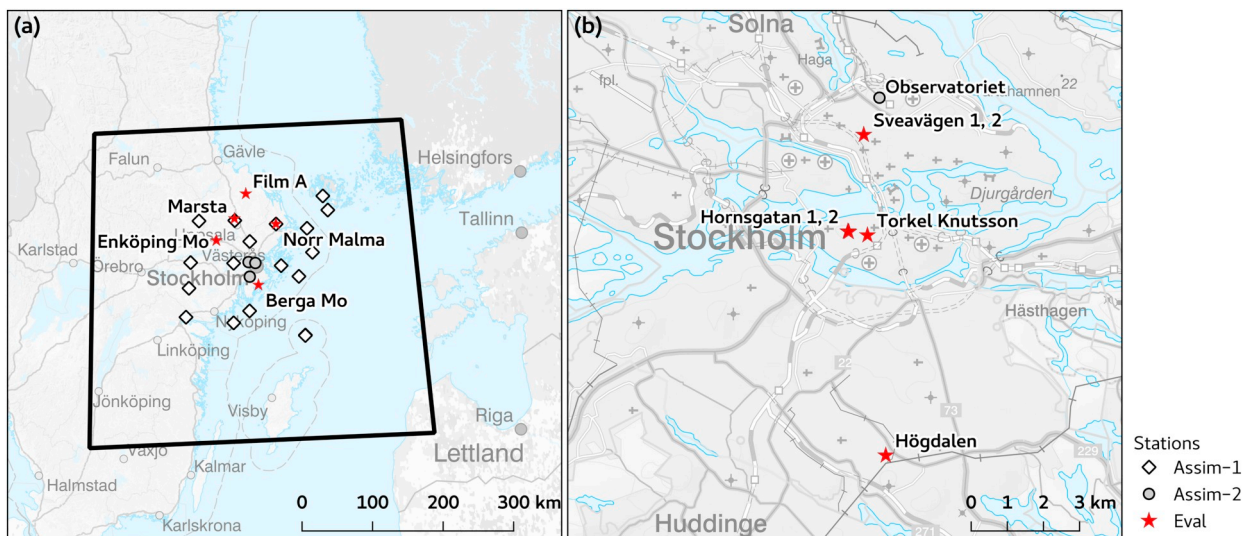


Fig. 2. (a) Modelling domain covering part of the Swedish territory and the Baltic sea with the location of the synoptic stations that were assimilated (“Assim-1” as rhombs) and those that were deactivated in the scenario runs (“Assim-2” as circles). (b) Close-up over the central area of Stockholm. The stars (“Eval”, with names given in bold) in both images mark the weather stations used in the evaluation over (a) rural and (b) urban sites. Note that the location of some stations cannot be distinguished at this scale because of their proximity.

surfaces (roofs, roads and walls), which enables a more accurate simulation of the fluxes to the atmosphere than modified-vegetation models (see review by [Grimmond et al., 2011](#)). The trapping of long- and shortwave radiation by the canyon, including the shadowing effect, are taken into account based on the geometrical description of the ‘Town’ tile (e.g., building density and height, road direction and aspect ratio of canyons).

Over water (‘Lake’ and ‘Sea’ tiles) diagnostic quantities at 2 and 10 m above ground are interpolated between the atmospheric forcing variables and the surface temperature and humidity. Over vegetated areas (‘Nature’), the coupling between the surface and the atmosphere is attained with the surface boundary layer scheme, which has been shown to improve performance in night-time stable conditions ([Masson and Seity, 2009](#)). Over urbanized areas (‘Town’) diagnostic quantities at 2 m are represented by the street canyon values of temperature and humidity, while the 10 m wind is diagnosed as over ‘Lake’ and ‘Sea’ tiles. Following [Bengtsson et al. \(2017\)](#), only one patch of nature is considered for simplification in ISBA, which aggregates the parameters for all vegetation types existing in each grid cell. Nature in the ‘Town’ tile is simulated by ISBA as ‘Garden’, which implies a simplified definition of physiography but, on the other hand, allows an enhanced interaction between the impervious surfaces and the vegetative canopy within the street-canyon (e.g. shading effects).

2.2. Model setup

2.2.1. Computational domain

The modelling domain displayed in [Fig. 2](#) consists of 240×240 gridpoints with a grid spacing of 1 km, thus covering 57,600 km², and 65 vertical levels. In order to allow for multiple years of simulations and sensitivity studies, the horizontal extent was limited and a cubic grid was applied. The domain was centred over the Stockholm city, and adjusted taking into account local topography and water bodies.

2.2.2. Time period

For the evaluation of model performance ([Section 3.1](#)) the years of 2006, 2007, 2012, 2013 and 2014 were selected. Model simulations for this 5-year period were carried out at 1 km resolution over Stockholm within the scope of UrbanSIS, a proof-of-concept project within the Copernicus Climate Change Service (C3S). More information can be found in [Gidhagen et al. \(2020\)](#), with results available online ([url1, n.d](#)) for visualization and download.

Aiming to assess the impact on urban temperature due to changes in physiography ([Section 3.2](#)) the warmest season in the 5-year period was selected as baseline conditions. This corresponds to the summer (JJA) of 2014, which encompassed a heat wave in the period 7–10 July with daily maximum observed air temperature above 25 °C.

2.2.3. Initialization

The atmospheric state for the dynamical downscaling is initialized by using the so-called blending feature ([Derková and Belluš, 2007](#)) of the shared ALADIN-HIRLAM system. In this approach, the large-scale state is taken from UERRA-ALADIN reanalysis (that is also used as lateral boundary condition as described in [Section 2.2.4](#)), while the small-scale state is provided by the previous 6-hour forecast from HARMONIE-AROME. The blending can be expressed with the following equation:

$$I = G^H + (A_{LOW}^U - G_{LOW}^H)_{HIGH}$$

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 $HIGH$ stands for the projection on the full high-resolution. For the surface fields, a surface data assimilation scheme ([Giard and Bazile, 2000](#)) is employed using optimal interpolation with CANARI ([Taillefer, 2002](#)). 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.

2.2.4. Boundary forcing

For the meteorological lateral boundary conditions we employ the UERRA-ALADIN reanalysis ([Ridal et al., 2016](#)). This European regional reanalysis uses the ALADIN NWP model together with the surface model SURFEX. The dataset extends over the period from 1961 to 2019 and has a resolution of 11 km horizontally and 65 levels up to 10 hPa vertically. In the reanalysis, a three-dimensional variational data assimilation is applied. The following observations are assimilated: conventional observations which include synoptic stations, ships, drifting buoys, aircraft observations and radio soundings. For surface data assimilation, the same method with CANARI ([Taillefer, 2002](#)) is applied as above. Only synoptic observations are used to analyse 2-m temperature (T2m), 2-m relative humidity and snow water equivalent.

2.2.5. Observations

The observation sites considered in this study are shown in [Fig. 2](#). For the surface data assimilation, near-surface temperature, relative humidity and snow water equivalent observations from surface synoptic and airport stations were used. These data were retrieved from the Meteorological Archival and Retrieval System (MARS) at the European Centre for Medium-range Weather Forecasts (ECMWF). Twenty stations are available in the Stockholm region, as illustrated with rhombs and circles in [Fig. 2](#). For allowing the simulation of scenarios with changed land surface, the stations situated in the urban area were removed from the

Table 1

Surface description data sources used in the construction of a refined physiography database for the baseline simulation.

Data type	Product	Spatial resolution (m)	Source	Reference
Spatial coverage of land cover types	Copernicus Land Monitoring Service: Urban Atlas 2012	—	Copernicus	url3, n.d
Building polygons	OpenStreetMap	—	Open street map contributors	url4, n.d
LAI of vegetation	Copernicus Global Land Service	300	Time-series of satellite data (PROBA-V)	url5, n.d
Building and tree heights	Swedish Forest Agency	12.5	Lidar measurements	url6, n.d

assimilation (circles in [Fig. 2](#)): Observatoriekullen (WMO id 2484), Bromma (WMO id 2464) and Tullinge (WMO id 2469). In-dependent stations used for the evaluation are marked with a star in [Fig. 2](#) (and listed in [Table A1](#), in annex).

2.2.6. Refined baseline physiography

Surface physiography is described in HARMONIE-AROME by the European, 1 km resolution, land cover database ECOCLIMAP-II ([Faroux et al., 2013](#) and [url2, n.d](#)), version 2.2. An analysis of this database over Stockholm revealed an insufficient level of detail in the description of the city's building density and extension, the urban green coverage, the Baltic Sea coast line and the lake Mälaren, which constitute distinguishing characteristics of this urban landscape. Refined physiography representing baseline surface characteristics was produced using the open-access products shown in [Table 1](#). The selection criteria for these data sources were the accuracy, resolution and availability of information. Vector data was gridded at a resolution of $25 \times 25 \text{ m}^2$, re-classified to match the tiles and patches required by SURFEX and then aggregated to produce fractions of each type of land-use at a final spatial resolution of 0.0042° (approximately $240 \times 460 \text{ m}^2$) over Stockholm. Descriptions of buildings, such as height and ratio of wall area to horizontal area, were made for individual buildings and subsequently averaged for each grid cell. Typical values of Leaf Area Index (LAI) for different types of urban vegetation, as well as the seasonal variation of LAI, were retrieved from Copernicus Global Land Service.

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

In [Fig. 3](#) the percentage of land covered by water and impervious surfaces in the original ECOCLIMAP-II is compared with the new refined physiography. The new dataset allows cells to be partially represented as water or urban areas, enabling it to capture the interface land/water more realistically. Also, the intra-city gradients of building density, as well as vegetation fraction, both in the city and outskirts, are much more detailed in the refined physiography.

The differences between original and refined physiography in terms of area per land-use type are specified in [Table 2](#). The largest relative change can be seen for buildings and other impervious surfaces.

2.3. Urban planning scenarios

This study evaluates the sensitivity of the urban air temperature in Stockholm to changes in land-use due to on-going/planned densification and expansion. For this purpose, two urban planning scenarios have been developed in collaboration with Stockholm City. The first represents the city's master plan for 2030, while the second was calibrated against the regional development plan for 2050 ([Table 3](#)).

The scenarios were produced by transforming natural environments and urban vegetation into buildings and roads until the official target of the corresponding plan was reached. For the year 2030, the areas designated for development in the master plan of Stockholm city (see [Fig. 4a](#)) were modified until 140,000 new homes ([City of Stockholm, 2018](#)) were attained. The scenario for 2050 (see [Fig. 4b](#)) uses the 2030 plan as a starting point. Nature and urban green areas are then iteratively transformed, starting close to existing built areas and proceeding until reaching an area corresponding to the target number of new homes in each municipality (600,000 new homes in total, based on supplement material from the report [Stockholms Läns Landsting, 2018](#)). Nature and agricultural areas were transformed before parks and other planned green areas. Protected areas such as nature reserves were excluded.

For all areas shown in [Fig. 4](#) (orange and purple polygons), a maximum of 40% green areas (nature, parks or gardens) was specified. Where this threshold was exceeded, the green area was reclassified to represent buildings (70%) and roads (30%). By setting a maximum fraction of green surfaces within the development areas, changes were made only in areas that are not already dense. For the definition of urban vegetation we have assumed that if more than 15% of a grid cell area was covered by impervious surfaces and at least 5% by buildings, all vegetation within that cell was classified as urban type ('Garden'), resulting in an improved simulation of the exchanges with the built-up environment (as explained in [Section 2.1.2](#)).

[Fig. 5](#) depicts the resulting expansion and densification of the city and its region.

Default ECOCLIMAP values were used to prescribe the anthropogenic heat released from buildings, traffic and industry. For the scenarios, the anthropogenic heat fluxes were parameterized as in the baseline simulation. Larger and denser urban areas release more heat to the atmosphere due to increased human activity. However, we did not take into consideration the effect of technological innovation (better insulation and more efficient ventilation and air conditioning systems) on future fluxes.

As mentioned in [Section 2.2.5](#), selected meteorological stations were removed from the default list of assimilated observations as a way of permitting the simulation of land-cover scenarios. We should also note that the boundary data provided by the ALADIN NWP

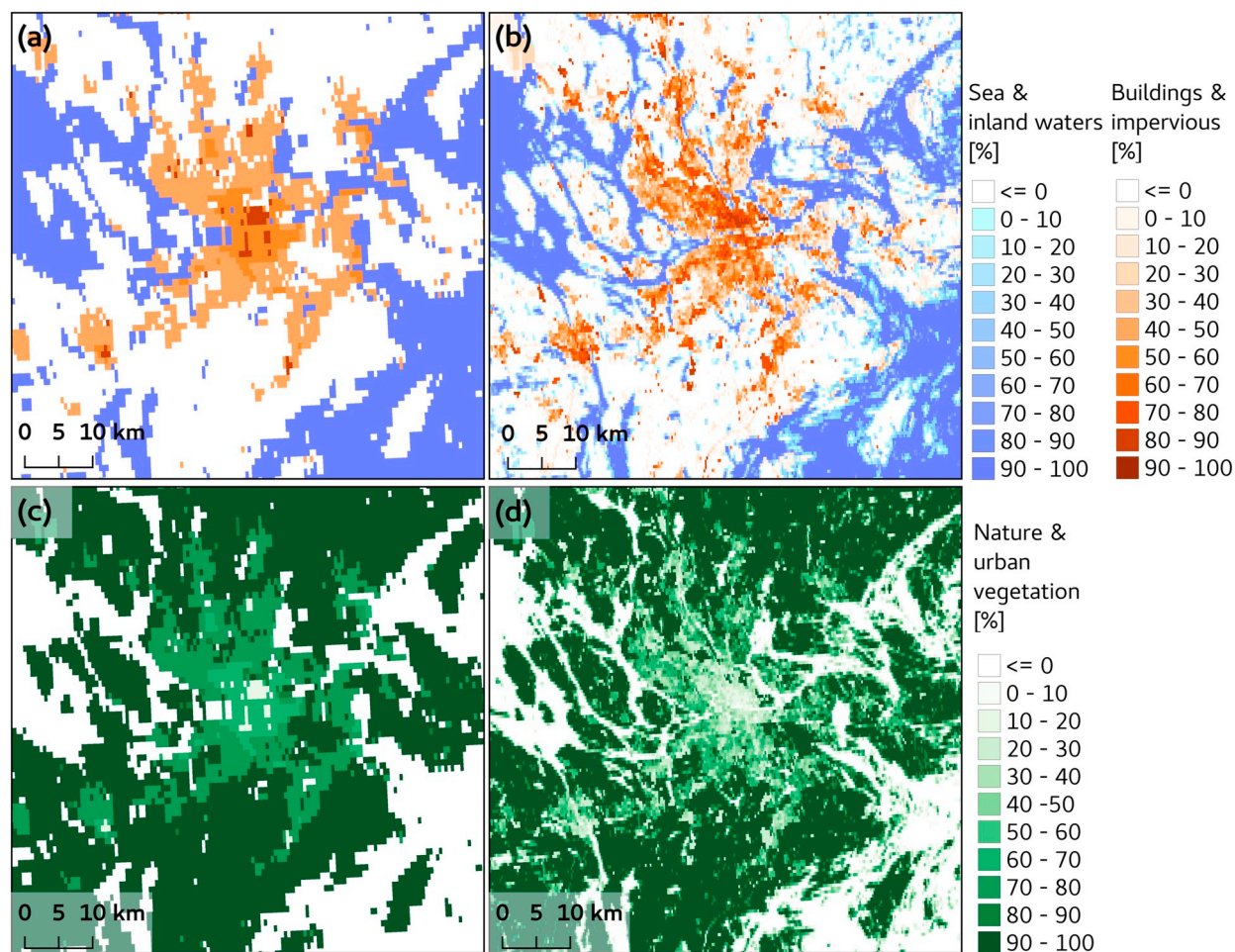


Fig. 3. Comparison between the default ECOCLIMAP-II (a and c) and the refined physiography (b and d). The upper panel shows the percentage of sea and inland water together with buildings and other impervious surfaces, while the lower panel maps the percentage of natural environments and urban vegetation.

Table 2

Comparison of surface area per land-use type in the default ECOCLIMAP-II database and the refined physiography (considering the entire domain shown in Fig. 3).

Physiography database	Sea & inland waters [km ²]	Buildings & other impervious [km ²]	Nature & urban vegetation [km ²]
ECOCLIMAP-II	1300	360	3226
Refined	1260	402	3127

Table 3

General description of the scenarios.

Scenario	Description	Year	Area affected	Transformed or densified area
Stockholm city 2030	- Calibrated against the official target of 140,000 new homes, including one of Europe's largest urban development areas: the 'Stockholm Royal Seaport' (City of Stockholm, 2018; url7, n.d) - Building densification reduces existing vegetation	2030	City	14 km ²
Stockholm region 2050	- Calibrated against the target of 600,000 new homes specified in the regional development plan (Stockholms Läns Landsting, 2018; url8, n.d) - Strong conversion of nature into new built-up areas	2050	Region	96 km ²

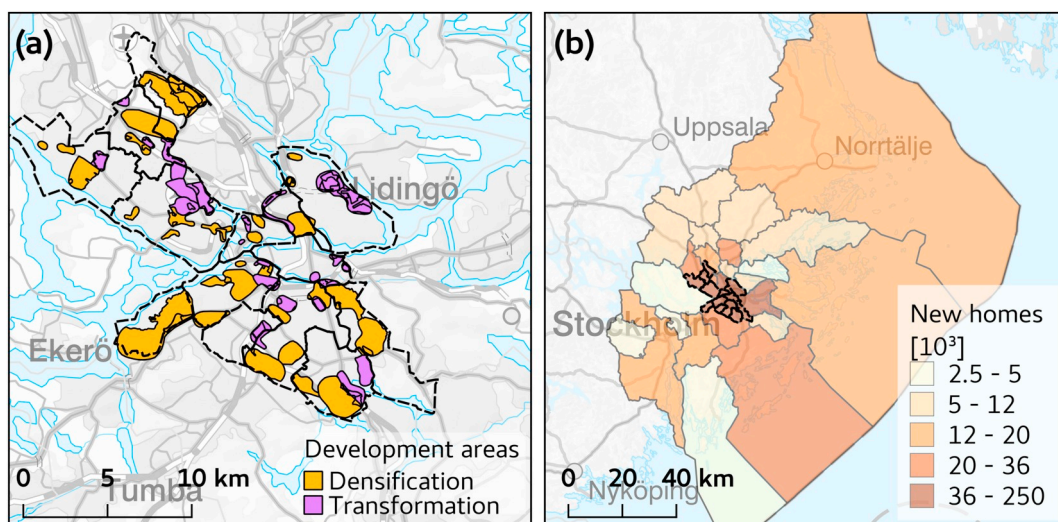


Fig. 4. The dashed black lines show the area administered by Stockholm city. In (a) the coloured areas are designated for densification or transformation in the master plan for 2030 ([url7, n.d.](#)), while (b) shows the number of new homes per municipality in the Stockholm county planned for 2050 ([url8, n.d.](#)).

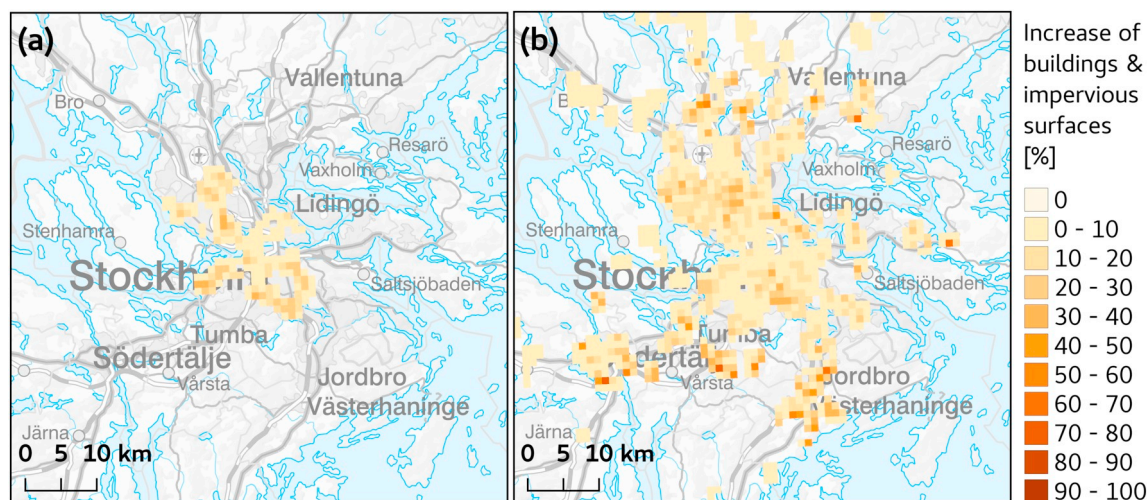


Fig. 5. Increase in buildings and impervious surfaces for scenarios (a) “city 2030” and (b) “region 2050”.

model (see 2.2.4) was kept constant in the scenarios, which means that no effects of changed physiography are present in the lower resolution ($11 \text{ km} \times 11 \text{ km}$) climate forcing. Although the consequences of this simplification are not evaluated in this paper, we don't expect an important influence on the 1 km grid resolution results.

3. Results and discussion

Section 3.1 describes the evaluation of model accuracy. Section 3.2 details the assessment of the results obtained for the scenarios, focusing on the spatial gradients of air temperature across the city (3.2.1), the average diurnal profile of temperature (3.2.2) and an indicator of potential heat stress (3.2.3).

3.1. Model performance evaluation

The quality of model results was assessed by comparison against meteorological observations carried out at 6 urban weather stations, including one located in an industrial area in the outskirts of Stockholm, and five more stations in rural areas, as described in Table A1 (in annex) and previously shown in the maps of Fig. 2. Note that in Torkel the instruments are located on a roof-top mast.

The statistical analysis of modelled air temperature is presented in Table 4 for 3 different time slices: the full 5-year period, the summers of the 5 years and the summer of 2014. In addition, for the latter period also the simulation without assimilation over the

Table 4

Statistical evaluation of model performance ordered as: “5 years”/“JJA 5 years”/“JJA 2014”/“JJA 2014 without assimilation”. Metrics: mean bias (MB), root mean square error (RMSE), Pearson correlation coefficient (r) and index of agreement (d_r). Both model and observations are based on hourly T2m data, except for Torkel where the second lowest model level (approx. 20 m above ground) was used. Mean and standard deviation are shown separately for the entire, the urban and the rural samples of stations.

Site group	RMSE [°C]	r [–]	d_r [–]
Mean	1.52/1.49/1.47/1.55	0.98/0.95/0.97/0.96	0.92/0.84/0.87/0.86
St.Dev.	0.30/0.29/0.33/0.31	0.00/0.01/0.01/0.01	0.02/0.03/0.03/0.03
Urban mean	1.28/1.26/1.19/1.32	0.99/0.96/0.97/0.97	0.93/0.85/0.89/0.88
Urban St.Dev.	0.17/0.17/0.10/0.20	0.00/0.01/0.00/0.00	0.01/0.02/0.01/0.02
Rural mean	1.80/1.76/1.80/1.82	0.98/0.94/0.96/0.96	0.90/0.82/0.84/0.84
Rural St.Dev.	0.14/0.12/0.13/0.16	0.00/0.01/0.00/0.00	0.01/0.04/0.03/0.03

city is shown, since this is the dataset that constitutes the baseline for the sensitivity analysis carried out in Section 3.2. In the evaluation, all model data is based on hourly average T2m, except for Torkel where the second lowest model level was extracted (corresponding to approximately 20 m above ground). The statistical metrics for the 11 sites is given in Table A2 in annex.

Willmott et al., 2012 refined index of agreement (d_r) equals 0.92 in average for the 11 sites over the full period. This result indicates that the sum of the magnitudes of the differences between the predicted and observed deviations about the observed mean is very small compared with the sum of the observed deviation magnitudes. Despite some decrease in accuracy if only the summertime is evaluated, d_r is well above 0.8 when focusing on the summer of 2014. In general, a warm model bias (0.7 °C in average) is found in JJA 2014, except for the rural stations of Norr Malma and Marsta where the model tends to underestimate the air temperature.

Independently from the time period, or the site, there is a strong linear relationship between computed and observed temperature. While this high correlation is not affected by the local deactivation of the assimilation, there is some increase of both the bias and the error when urban observations are not assimilated by HARMONIE-AROME. As expected, this occurs especially over the city. It is worth noticing the lower model performance over nature areas, with a 5-year average RMSE of 1.80 °C, against 1.28 °C in the urban sites.

The importance of station siting is evident in the two observation datasets acquired at Sveavägen street in central Stockholm. Although the model performs very well when compared against Sveavägen 1, it shows a poorer performance for Sveavägen 2 in the summer, despite the fact that the two thermohygrometers are very closely located and should, therefore, represent similar micro-environmental conditions if radiation effects on measurements can be excluded. The uncertainty in the observations (caused by technical issues or related to the sensor placement) should not be disregarded, especially within urban environments.

The Taylor diagram (Taylor, 2001) in Fig. 6 provides a good illustration of how model performance varies with site and season over the 5 years. The highest observed seasonal standard deviation was registered in the spring (6.3 °C), a tendency that is followed by the model at the different locations. However, it is in the autumn that the closest match between modelled and measured variability is found, especially in the city. The most striking aspect distinguishing the two land-use types is the tendency for rural sites to present larger model variability than the one observed.

Fig. 7 presents the observed and modelled mean diurnal variations of air temperature over different seasons in the two urban meteorological masts. The profiles are shown only for the year of 2014 due to the focus of this work. The computed diurnal cycle generally follows the observed trend. The comparison yields a small cold bias in the spring starting at early morning (around 3:00 UTC) and extending up to 9:00 at the industrial outskirts of Högdalen. This effect is visible at the city centre station of Torkel up to midday, both in spring and summer. The underestimation extends over the nocturnal period in the colder seasons. Since the maximum temperatures at daytime are, in general, in good agreement with the measurements, the morning bias indicates that the model takes more time to warm-up the urban atmosphere than what is expressed by the observations. This systematic offset may be associated to the interaction between clouds and radiation, the prescribed aerosol concentration in the model, or to the definition of the radiative and thermal properties of the impervious surfaces (buildings and roads).

3.2. Planning scenarios analysis

The analysis of the scenarios aims at identifying the effect of planned land-use changes on the spatial variation and temporal evolution of the urban temperature of future Stockholm. In particular, we are interested in: (i) quantifying the change in temperature caused by the new built-up areas (formerly vegetated) and (ii) finding if there is a wide-spread effect that can impact even the city centre where no significant construction is foreseen.

3.2.1. Spatial variation of temperature

The analysis of the meteorological data produced by HARMONIE-AROME revealed a strong interaction with the surface characteristics. As an example, Fig. 8 illustrates the 2014 average summer UHI in Stockholm, with an urban-to-rural temperature gradient in the range of 2 to 3 °C, amounting to approximately 4 °C at night-time, in agreement with observations. In addition, the variation of intra-city temperature is also visible, in response to varying fractions of the underlying urban vegetation (such as parks and lawns), lakes and impervious areas (buildings and roads).

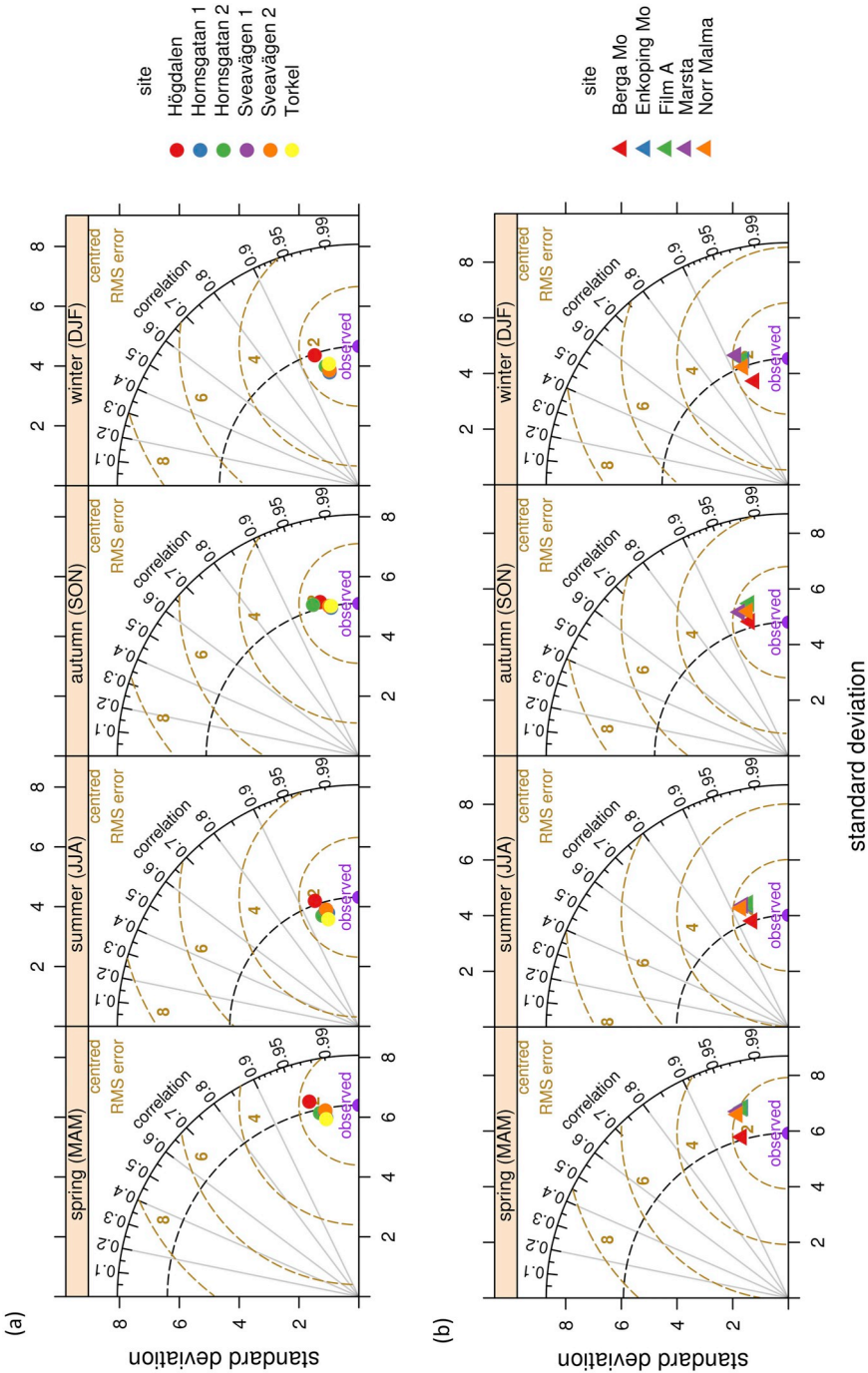


Fig. 6. Taylor diagram of seasonal model performance over urban (a) and rural (b) sites in the 5-year period. The statistics correspond to T2m, except for Torkel where the second lowest model level was used. The observed variability is marked as ‘observed’ on the x-axis.

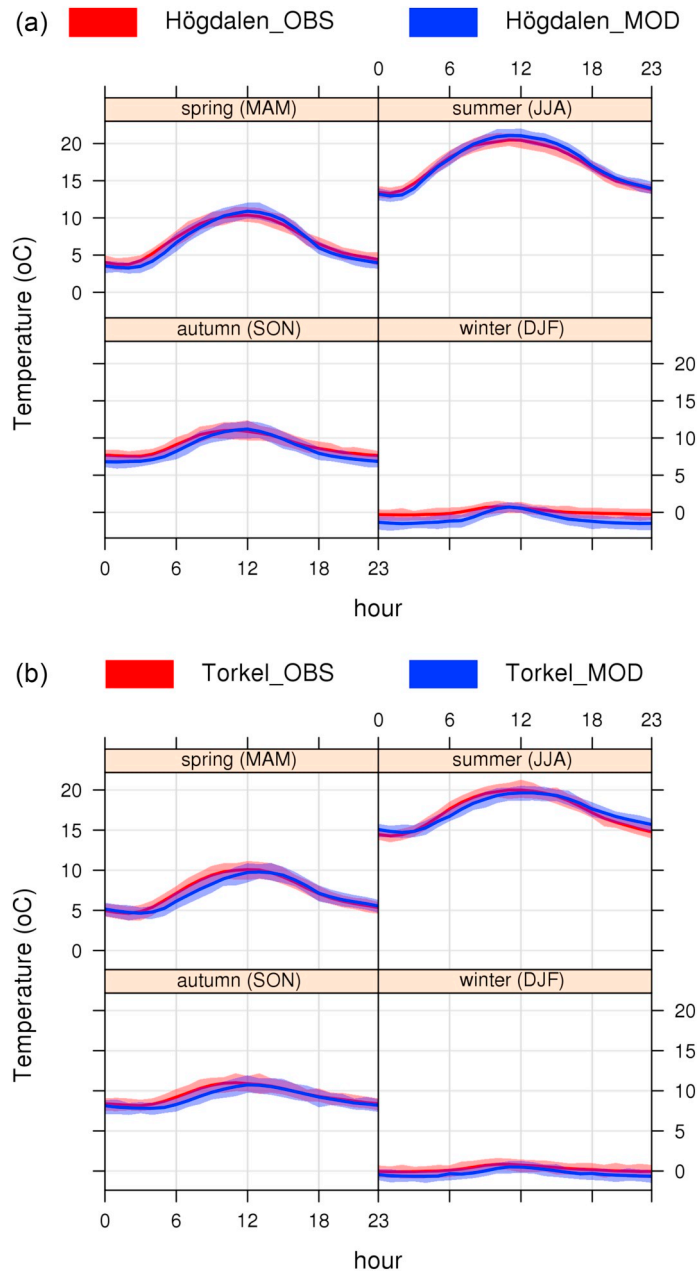


Fig. 7. Observed (OBS) and modelled (MOD) diurnal variation of air temperature per season in 2014 at (a) Högdalen and (b) Torkel. Mean line and the 95% confidence interval in the mean are shown. Time is in UTC.

In Fig. 9, the differences in average T2m in JJA 2014 between the scenarios and the baseline are plotted. To avoid presenting minor variations caused by numerical sensitivity together with the relatively short averaging period, only changes larger than 0.2 °C are shown. This threshold was chosen from inspection of the data in areas without any change of physiography. Taking as reference the summer of 2014, the scenarios bring an average warming of 0.29 °C and 0.46 °C, respectively for years 2030 (Fig. 9a) and 2050 (Fig. 9b), reaching up to 1.35 °C in the latter over specific zones. The warmer atmosphere found for 2050 is a result of the more intense densification prescribed in this development plan. Also, because of its regional coverage, the temperature change is more widespread than in 2030. An important conclusion from these results is that the temperature increments are spatially limited to the densified or transformed areas in both plans, a feature that will be further analysed below. In Fig. 9c, the impact of the 2050 scenario is presented only for the night. It is found that in some areas where the physiography has been modified, the average nocturnal temperature increment is up to 0.5 °C larger than the 24 h average increment. This night-time effect is explained by the slower cooling of these new urban environments in the late afternoon and evening in comparison to the original vegetated surfaces, basically the same process that causes more pronounced UHIs on calm clear nights (e.g. Oke et al., 2017).

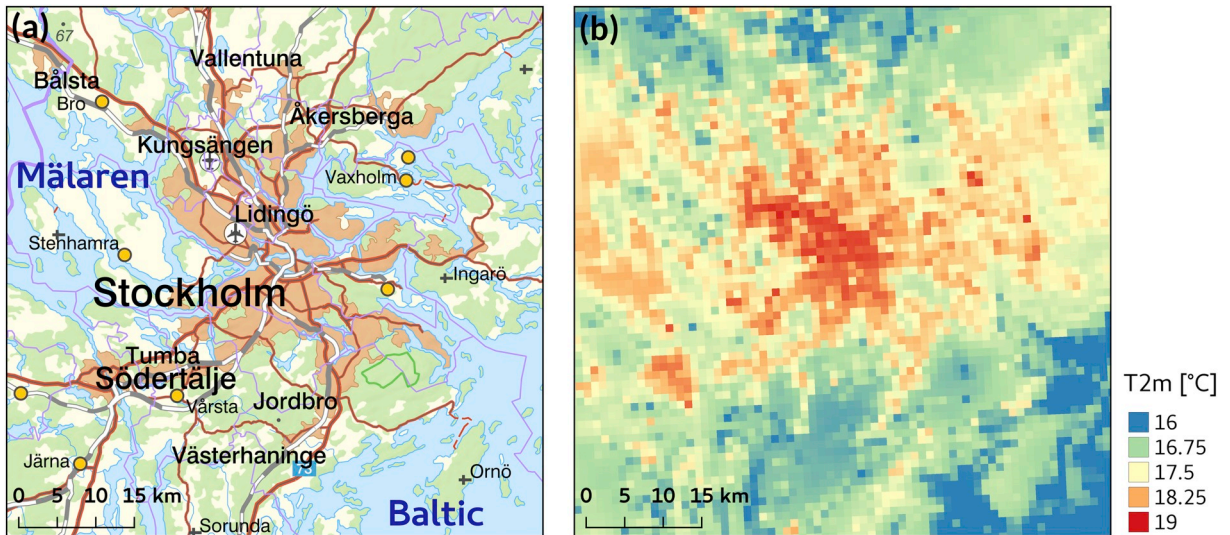


Fig. 8. (a) Map of Stockholm region showing the urban areas (light orange), main roads (dark orange), nature areas (green), cropland (light yellow) and the Baltic sea, the lake Mälaren and other smaller lakes (in blue). (b) Mean T2m in JJA 2014 (baseline) as simulated by HARMONIE-AROME over Stockholm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

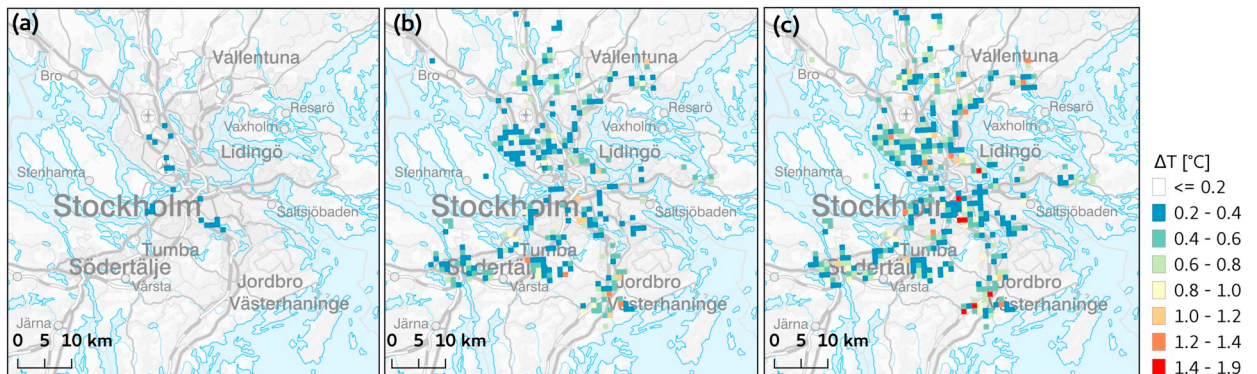


Fig. 9. Difference in mean T2m between the scenarios and the baseline in JJA 2014. (a) “City 2030”, (b) “Region 2050” and (c) “Region 2050” at night-time (02–07 UTC).

Two main aspects arise from the analysis of Fig. 9 that ask for additional investigation, the first being the intensity of the computed warming in relation to the magnitude of the urbanization, and the second the spatial extent of this effect. We have firstly analysed the sensitivity of average T2m to the degree of urban densification, expressed here as the conversion rate from natural environments (excluding water) or urban vegetation to buildings or impervious surfaces. Fig. 10 presents the variation of the temperature increment with the densification planned for 2050, only including the grid cells with modified physiography. Despite the wide spread of data and the weak linear relationship ($R^2 = 0.34$), stressing the necessary caution in the interpretation of these results, one can take an indicative average temperature increase of $0.14\text{ }^{\circ}\text{C}$ per 10% of densification. The significant data spread is expected given the impossibility of isolating the interaction between grid cells (as analysed in Fig. 11), but also due to the fact that the physiography of each transformed grid cell is composed of different combinations of vegetation and urban surfaces that will imprint a specific temperature signal. The numerical sensitivity of the analysis for values close to zero ($< 0.2\text{ }^{\circ}\text{C}$) should also be taken into consideration, in combination with the short averaging time and the analysis of a single climate model realization.

The second aspect analysed is related to the largest temperature increases occurring mostly over grid cells where natural environments have been urbanized, which points to a localized warming effect. The blue squares in Fig. 11 mark the 1 km^2 model cells with a temperature increment above $0.2\text{ }^{\circ}\text{C}$ and unchanged physiography. This shows that only in 19 cells there was a significant warming effect ($> 0.2\text{ }^{\circ}\text{C}$) that has been caused by a neighbouring transformed area. This effect is also more evident in the southern part of the domain, where the transformation is more intense (compare with Fig. 4b and Fig. 5b).

Since the most central parts of the city are very dense already today, there is hardly any densification expected there in the future and, at the same time, no significant temperature increase can be seen in the results previously shown in Fig. 9. This demonstrates the limited area of influence that densification has on temperature, according to our model results. Stockholm city is located at the border between the large lake Mälaren and the Baltic Sea and has expanded over 14 islands, benefiting from relatively large forested areas

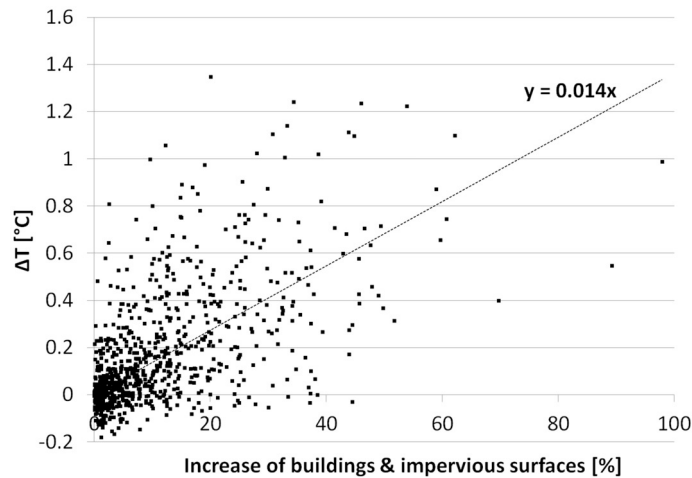


Fig. 10. Temperature change caused by an increased percentage of the land covered by buildings or other impervious surfaces. All computational cells of scenario “region 2050” where land-use has changed are shown.

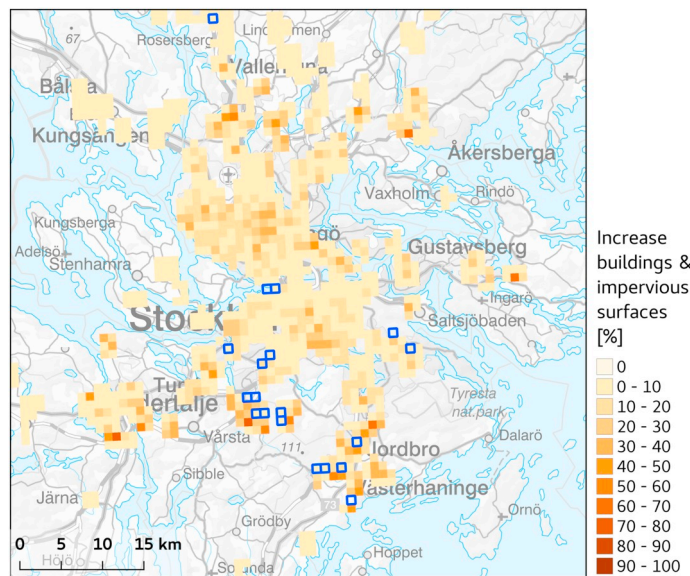


Fig. 11. Computational cells where buildings and other impervious surfaces have not changed, but temperature has still increased by more than 0.2 °C, are marked by blue squares. In addition, the urbanization rate is shown in the colour scale. The results pertain to the scenario “region 2050”. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

close to the city. These conditions provide good exchange of fresh air with the surrounding natural environments that, to some extent, explain the absence of a noticeable temperature change over the city centre, despite extensive densification in the region around.

The area of influence of urban densification has implications for the homogenization of temperature measurements, which is the process of removing non-climatic changes when studying long measurement series. The well-known temperature measurement series at the Observatorielunden weather station in central Stockholm, dating back to 1754, has been homogenized in the study by [Moberg et al. \(2002\)](#) considering urban warming. From 1967 to 1998, when the city expanded while the centre had already a consolidated built-up infrastructure, the applied monthly bias correction was kept constant. Despite the different time frame of our study (and particularly the focus on a warm summer), the present results are in line with the decision of [Moberg et al. \(2002\)](#) of disregarding the local contribution of the UHI over the temperature in the older city centre. Since only limited densification has taken place in the vicinity (within a radius of 1 km) of Observatorielunden, the effect on this site from the expansion of Stockholm should not have been significant during the last decades.

3.2.2. Diurnal variation of temperature

Another aspect of interest is the comparison of the average diurnal profiles. A point-wise analysis is carried out over a number of locations for which model results were extracted. The rationale behind the selection of these spots was to describe areas where more

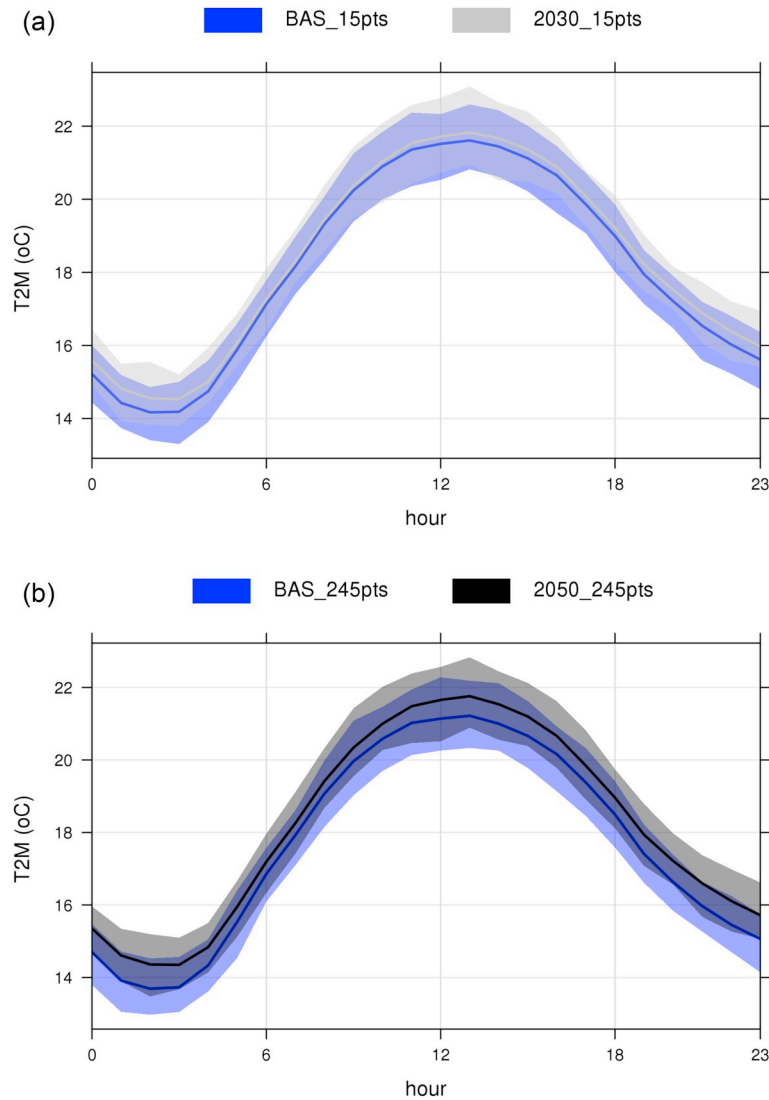


Fig. 12. Mean diurnal variation of T2M in JJA over a set of extraction points for the baseline (BAS) and scenarios 2030 and 2050. Note that distinct extraction points were processed in the two graphs. The points were selected over a sub-domain covering the city and its outskirts (latitude 59.1–59.4 and longitude 17.8–18.1). Mean line and the 95% confidence interval in the mean are shown. Time is in UTC.

than 50% of the grid cell area was converted to impervious surfaces, resulting in 15 and 245 points respectively in 2030 and 2050. The comparison against the baseline is shown in Fig. 12.

Note that the baseline diurnal profiles in Fig. 12a and Fig. 12b are different because of the selection of different points for the extraction. Due to this, the average baseline temperature is, in fact, 0.4 °C warmer over the points selected for 2030 than for those considered in 2050.

On the contrary, with a mean temperature difference of only 0.2 °C, the two scenario profiles are quite similar at the selected grid cells. This result confirms the conclusion taken in Section 3.2.1 that the average intensity of the resulting warming is better explained by the magnitude of the local land-use changes (e.g., fraction of grid cell surface converted into impervious), than by the spatial extent of the area built. Consequently, and despite the more intense expansion/densification plan for the region in 2050, similar changes in point-wise temperatures were found compared to 2030. Likewise, different neighbourhoods in the baseline exhibit temperature gradients that can even exceed the average warming induced by the construction scenarios (as shown by the comparison of the two baseline profiles).

3.2.3. Number of hot days

The indicator selected to analyse the potential impact of densification on heat stress is the number of hot days (NHD), defined here as the days with mean air temperature above 16.04 °C. This temperature threshold corresponds to the 75th percentile of T2m over Bromma, in Stockholm, from April to September in present climate, as simulated by HARMONIE-AROME in UrbanSIS (for more

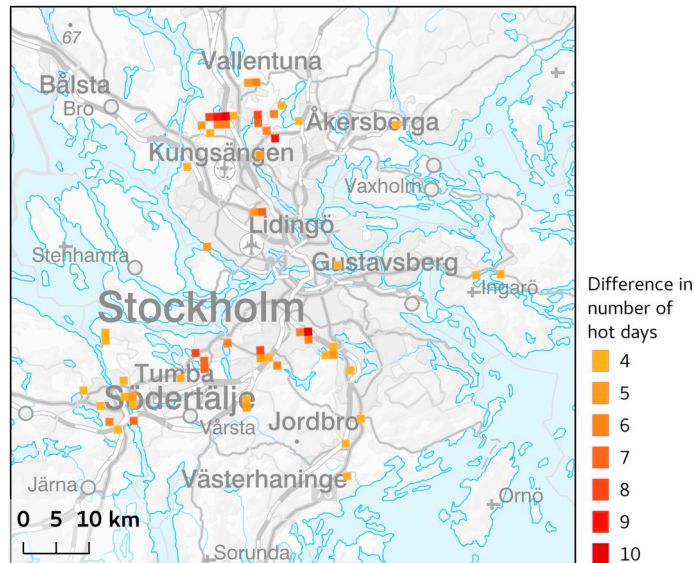


Fig. 13. Difference between “region 2050” and baseline in the number of days with mean air temperature above the 75th percentile of the 5-year mean summer T2m in Stockholm city. Following a similar assumption as in the analysis of Fig. 9, only differences above 3 days were considered.

details see Gidhagen et al. (2020)). The 75th percentile was chosen based on the health effect assessment in nine European cities carried out by DeDonato et al., 2015, which shows that during 2004–2010 the heat-attributable mortality in Stockholm increased by 12% for days with mean temperatures between the 75th and 99th percentiles. Only grid cells with an NHD above or equal to 3 were considered, in line with the analysis in Fig. 11 where a cut-off of 0.2 °C was considered. Because of this minimum threshold, no significant differences were found for “city 2030” (not shown). For 2050, Fig. 13 points to maximum increases of 10 hot days as predicted by the model. The comparison of the differences for 2050 in Fig. 13 with Fig. 9b shows that, while the noticeable warming over the S/SW region of the domain (city of Södertälje) increases the NHD by up to 6 in JJA, a lower impact is found over the S/SE corner (Västerhaninge and Jordbro). A similar longitudinal gradient is noticeable in the northern region. The comparison of temperature data for places inland and closer to the Baltic Sea indicates that the nearness to the sea mitigates the occurrence of higher temperatures and, consequently, diminishes the NHD value. This is also sustained by the nocturnal warming identified in Fig. 9c, which indicated that the night-time lower temperatures are more strongly impacted by urbanization.

4. Conclusions

Climate-resilient urban planning requires a more detailed understanding of the urban climate, and how it interacts with the city's physiography and anthropogenic activity. In addition to the validation carried out by Gidhagen et al. (2020), we demonstrate that the dynamical downscaling with a convection-permitting NWP model offers the capability to simulate from single season or even specific weather events to multi-annual periods over a limited area, delivering accurate intra-urban temperature gradients. This data provides information on spatial scales small enough to support detailed impact and adaptation assessment and planning.

With a mean bias of −0.22 °C when compared against 5 years of observations at 5 urban weather stations, the dynamical downscaling of the urban climate of Stockholm with the HARMONIE-AROME NWP system has shown to offer the required performance skills for the objectives of the study. The high-resolution modelled urban climate data reveals the thermal fingerprint of Stockholm expressed in the form of its UHI and intra-city temperature variations, which is associated to a complex combination of vegetated areas (mostly parks), lakes and varying building density.

Taking the summer of 2014 as baseline conditions, the results show that the existing urban/regional development plans for Stockholm would increase the air temperature over the newly urbanized areas (currently vegetated) by 0.29 °C and 0.46 °C, respectively in 2030 and 2050, in average for the summer. More intense urbanization in the long-term scenario leads to increased temperatures of up to 1.35 °C, and a widespread impact over the region where the intervention will take place. One should stress that this effect will be potentially intensified by climate change, estimated by Hoegh-Guldberg et al. (2018) in the order of 2–4 °C over Sweden (for a 2 °C global warming scenario). Understanding the added effect of urban development and climate change on Stockholm's climate, especially during the warm season, is the topic of research of an on-going study.

Although we have found that larger densified areas may influence the surroundings at a distance of up to 3 km, the warming effect of urbanization is mostly local, being in general confined to the $1 \times 1 \text{ km}^2$ grid cell where the conversion to impervious surfaces occurs. Due to its location in the proximity of the Baltic Sea, and the profusion of lakes and forested areas, Stockholm region benefits from the entrainment of cooling air from these natural environments. The localized warming identified in this work can, to a great extent, be explained by this effect, and cannot be extrapolated to inland dry cities with a lower rate of vegetation and water.

An increase in the number of hot days by up to 10 is predicted for 2050 (taking JJA 2014 as forcing conditions), with locations along the coast being less prone to temperature maxima, indicating a potential sea cooling effect. Although no relation with health effects was attempted in this work, the magnitude of this increase should stimulate the definition of specific heat exposure-response relations.

Contact with stakeholders in Stockholm and in other European cities has shown that high resolution climate data is useful to urban planners dealing with the urban adaptation to climate change. Implications to the health sector can also be of relevance, but more research is needed towards an improved use of fine scale weather and climate data in epidemiological studies focusing on urban environments.

Declaration of Competing Interest

The authors declare having no competing interests.

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Appendix A

Table A1

Characterisation of the weather stations used in the validation, under the responsibility of SLB-analysis (Stockholms Luft- och Bulleranalys at Stockholm City) and the Swedish Meteorological and Hydrological Institute (SMHI).

Site id	Location	Siting	Coordinates (lat, lon)	Sensor height (m)	Reference
Hornsgatan 1	City centre	W/E oriented street canyon with 7 storey buildings and no trees. Sensor on North side.	59.3172, 18.0484	2	SLB
Hornsgatan 2	City centre	Same canyon as Hornsgatan 1, opposite side.	59.3171, 18.0488	2	SLB
Sveavägen 1	City centre	NW/SE oriented street canyon with 7 storey buildings and trees along sidewalks. Sensor on West side. Approx. 100 m from Observatorielunden park.	59.3410, 18.0582	2	SLB
Sveavägen 2	City centre	Close to Sveavägen 1.	59.3410, 18.0582	2	SLB
Torkel Knutsson	City centre	Roof top of a 6 storey building.	59.3160, 18.0578	20	SLB, url9 , n.d
Högdalen	Outskirts	Industrial area surrounded by a small forest and buildings.	59.2612, 18.0618	5	SLB, url9 , n.d
Marsta	Rural	Cropland in the vicinity of Uppsala. 70 km NW of Stockholm's city centre.	59.9260, 17.5870	2	SLB, url9 , n.d
Norr Malma	Rural	Agricultural field surrounded by forest and in the vicinity of a lake. 64 km NE of Stockholm.	59.8324, 18.6312	2	SLB, url9 , n.d
Berga Mo	Rural	Small forest at the shore of the Baltic sea. 30 km S of Stockholm.	59.6557, 17.1121	2	SMHI, url10 , n.d
Enköping Mo	Rural	Agricultural field in the outskirts of Enköping city. 64 km NW of Stockholm.	60.2358, 17.9043	2	SMHI, url10 , n.d
Film A	Rural	Agricultural field surrounded by forests patches. 100 km N of Stockholm.	59.0688, 18.1184	2	SMHI, url10 , n.d

Table A2

Statistical evaluation of model performance ordered as: “5 years”/“JJA 5 years”/“JJA 2014”/“JJA 2014 without assimilation”. Metrics: number of observations (n), mean bias (MB), root mean square error (RMSE), Pearson correlation coefficient (r) and index of agreement (d_r). Note that some of the stations were not fully operational during the entire period. The fraction of predictions within a factor or two (FAC2) was consistently 1.0 and therefore is not shown. Both model and observations are based on hourly T2m data, except for Torkel where the second lowest model level was used. An evaluation of additional meteorological variables can be found in Gidhagen et al. (2020) and SMHI (2017).

Site id	n [–]	MB [°C]	RMSE [°C]	r [–]	d_r [–]
Hornsgatan 1	26,072/6596/2180/2180	−0.08/0.27/0.36/0.56	1.09/1.11/1.13/1.23	0.99/0.97/0.98/0.97	0.94/0.87/0.90/0.89
Hornsgatan 2	39,497/9985/1334/1333	−0.10/0.12/0.34/0.53	1.39/1.41/1.26/1.34	0.99/0.95/0.97/0.97	0.93/0.84/0.89/0.88
Sveavägen 1	26,134/6620/2208/2208	−0.59/0.16/0.24/0.37	1.33/1.11/1.14/1.19	0.99/0.96/0.97/0.97	0.92/0.86/0.89/0.89
Sveavägen 2	26,133/6624/2208/2208	−0.10/0.71/0.76/0.90	1.21/1.30/1.34/1.44	0.99/0.96/0.97/0.97	0.93/0.84/0.87/0.86
Torkel K.	43,322/11012/2208/2208	−0.21/0.16/0.04/0.16	1.10/1.10/1.03/1.05	0.99/0.96/0.98/0.98	0.94/0.87/0.90/0.90
Högdalen	43,370/10691/2208/2208	−0.19/0.49/0.19/1.11	1.57/1.55/1.26/1.68	0.98/0.94/0.97/0.97	0.91/0.83/0.88/0.84
Marsta	43,580/10822/2208/2208	−0.82/−0.58/−0.66/−0.63	2.06/1.78/1.75/1.75	0.98/0.94/0.95/0.95	0.89/0.82/0.84/0.84
Norr Malma	43,497/10766/2208/2208	−0.57/−0.09/−0.84/−0.89	1.81/1.71/1.80/1.81	0.98/0.93/0.95/0.95	0.90/0.81/0.83/0.83
Berga Mo	25,161/6187/1776/1776	0.55/1.47/1.48/1.55	1.68/1.98/2.06/2.12	0.98/0.95/0.96/0.96	0.90/0.75/0.80/0.80
Enköping Mo	26,267/6617/2206/2206	−0.07/0.57/0.62/0.60	1.72/1.62/1.67/1.66	0.98/0.95/0.96/0.96	0.91/0.85/0.87/0.87
Film A	43,578/11035/2208/2208	−0.05/0.60/0.51/0.52	1.73/1.71/1.74/1.74	0.98/0.95/0.96/0.96	0.91/0.85/0.87/0.87

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