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Impact of regional afforestation on climatic conditions in Copenhagen Metropolitan Area

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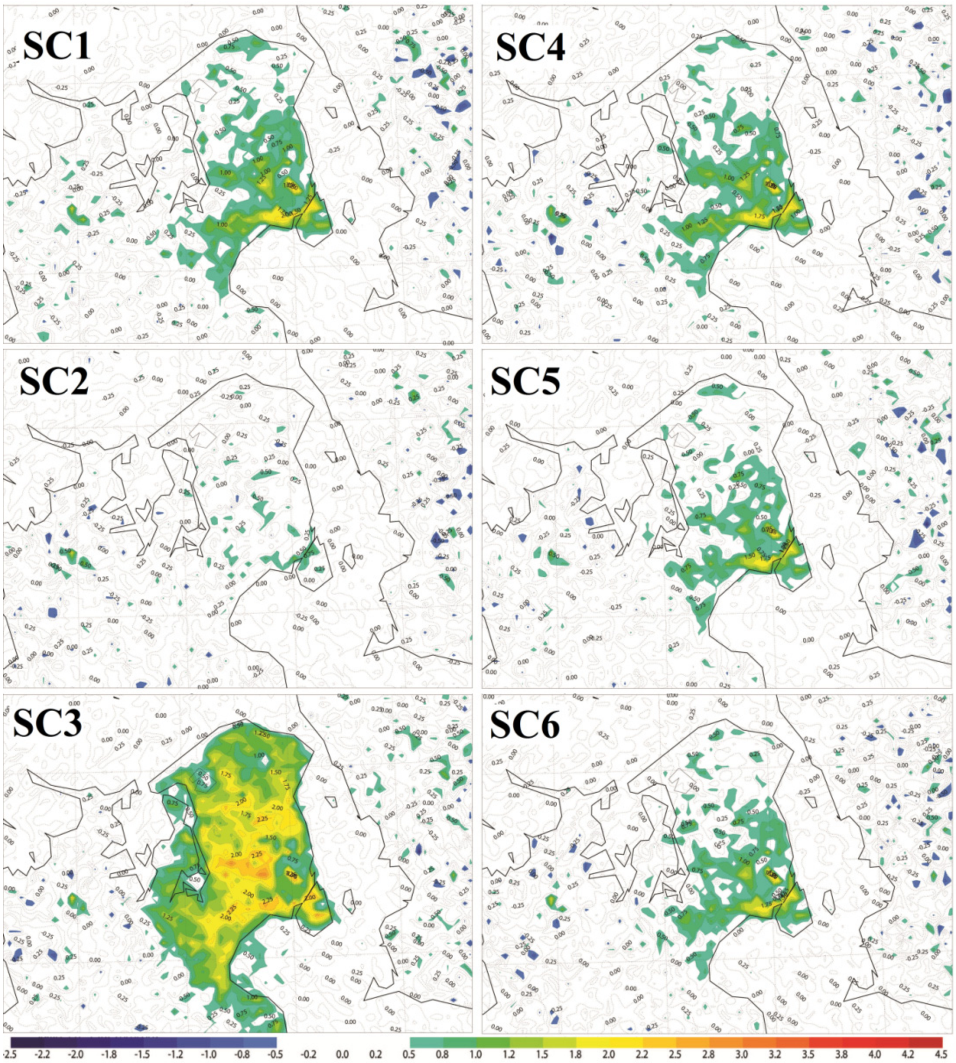

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Abstract

This study investigates the impact of forest and land-cover change on formation and development of temperature regimes in the Copenhagen Metropolitan Area (CPH-MA). Potential to modify the UHI effect in CPH-MA is estimated. Using 2009 meteorological data, and up-to-date 2012 high resolution land-cover data we employed the online integrated meteorology-chemistry/aerosols Enviro-HIRLAM (Environment – High Resolution Limited Area Model) modeling system to simulate air temperature (at 2 meter height) fields for a selected period in July 2009. Employing research tools (such as METGRAF meteorological software and Geographical Information Systems) we then estimated the influence of different afforestation and urbanization scenarios with new forests being located after the Danish national afforestation plan, after proximity to the city center, after dominating wind characteristics, and urbanization taking place as densification of the existing conurbation. This study showed the difference in temperature up to 3.25°C, and the decrease in the spatial extent of temperature fields up to 68%, depending on the selected scenario. Performed simulations demonstrated that well-positioned and well-sized afforestation at the regional scale can significantly affect the spatial distribution, structure and intensity of the temperature field. This study points to vegetation having practical applications in urban and regional planning for modifying local climatic conditions.

1. Introduction

Climate research and the understanding of the land cover – atmosphere interactions play an important role in planning urbanized areas and adapting them to climate change (CC).
Like most other places, European cities and metropolitan areas will face a range of climate–related challenges over the next decades that may influence the nature of urban life across the continent. Under future urbanization and CC scenarios the well-being and comfort of the urban population might become progressively compromised (IPCC 2007). In urban areas, the effects of the warming climate will be accelerated by combination of Urban Heat Island effect (UHI) and extreme heat waves (IPCC 2007; EEA, 2008).
The land cover composition directly influences atmospheric variability, and can either escalate or downscale the projected changes. (e.g., Pielke and Avissar, 1990; Claussen et al., 2001; Feddema et. al, 2005; Seneviratne et al., 2006).Vegetation, forest ecosystems in particular, are anticipated to play an important role in modulating local and regional climatic conditions, and to be vital factor in the process of adapting cities to warming climate (Pielke et al., 1989; Bounoua et al., 2002; Brovkin, 2002; Gálos et al., 2011).
Numerical weather prediction (NWP) systems are constantly developing and special focus is paid to high resolution modeling of urban areas. That is achieved by means of urban parameterization modules, e.g. the Building Effect Parameterization (BEP, Martilli et al., 2002) module, or Anthropogenic Heat Fluxes (AHF) in urban areas from Large scale Urban Consumption of energY (LUCY) model (Allen et al., 2010). These urban parameterization modules utilize existing local land use and land cover databases at different scales and resolutions.
Application of NWP models together with urban parameterization modules into urban planning efforts can possibly offer valuable insight into assessing the impact, consequences and optimizing the projected plans.

In mid 1980s, Denmark intensified its efforts in country afforestation, with the target of doubling Danish forest area from present 12% to about 25% in one forest rotation. This nation-wide program will continue in the near future. Danish afforestation program was based on several incentives, timber production and recreational needs of the society being the main ones (Naturstyrelsen 2000). However, potential effects of the designated afforestation on the formation of regional climate have not been investigated.

This project investigates the potential impact of various afforestation scenarios on the formation of the air temperature fields at 2m height in metropolitan areas, using situation in July 2009 in Greater Copenhagen Metropolitan Area (CPH-MA) as case. The project takes its point of departure in the historical but still respected green verge plan, *FingerPlan* for spatial development of the metropolitan area, and the afforestation plans for that region. The project employs the numerical weather prediction (NWP) and atmospheric chemical transport model Enviro-HIRLAM (Environment – HIgh Resolution Limited Area Model). Report presents also a methodological approach for adjusting the land cover data and integrating it into the Enviro-HIRLAM model.
The results of this study can be used for regional scale climate modeling and evaluation of projected changes in land cover due to urban and environmental planning efforts.

2. Methodology

The described approach can be applied in urban scale modeling with NWP-ACT (Numerical Weather Prediction-Atmospheric Chemical Transport) models running at high resolution. Approach can be used to study impact of land-cover and land-use on the local and regional scale climatic conditions, e.g. temperature regime, precipitation patterns, wind characteristics, and chemical species transport (e.g. ozone concentration). Methodology employs online integrated meteorology-chemistry Enviro-HIRLAM model (Environment – HIgh Resolution Limited Area Model), meteorological METGRAF software, and Quantum Geographical Information Systems (QGIS). Enviro-HIRLAM model is used to run simulations of meteorological conditions. METGRAF is used for extracting and plotting data from the output files generated by Enviro-HIRLAM model. GIS tools are used to process relevant local/regional land-use databases and prepare the modified input files for the Enviro-HIRLAM model, and further to perform the analysis of the results.

2.1. Enviro-HIRLAM: Environment – HIgh Resolution Limited Area Model

2.1.1. Model description

The Enviro-HIRLAM is a fully online integrated numerical weather prediction (NWP) and atmospheric chemical transport model (ACTM) system, used for forecasting and research of meteorological and chemical weather (Baklanov et al., 2008). The meteorological (hydrostatic mode) and chemistry model uses equations describing six processes: emission, advection, horizontal diffusion, vertical diffusion and dry deposition, convection and wet deposition, chemistry and aerosols (Korsholm et al., 2008). The system realization includes 6 steps which are: nesting of models for higher resolutions, improved resolving of boundary and surface layers characteristics and structures, different levels of urbanization improvement of advection schemes, implementation of chemical mechanisms, implementation of aerosol dynamics, realization of feedback mechanisms, and assimilation of monitoring data (Baklanov et al., 2008).

Modelling at the metropolitan scale in Enviro-HIRLAM model is carried out with the BEP module (Martilli et al., 2002) module. Urban area is represented as a mosaic of different urban districts. Each of the urban district is characterized by a combination of multiple streets and buildings that have constant widths, but different heights. The districts are represented by an array of buildings, located at the same distance from each other, having the same width, and similar thermo-dynamic characteristics. For simplicity the length of the street canyons is assumed to be equal or larger to the horizontal grid. The urban parameterization requires a set of different parameters for the ground, walls and rood surfaces as input. BEP module includes computing of contributions from every type of urban surface for the momentum, heat and turbulent kinetic energy equation as contributions of the vertical surfaces (building walls) as well as horizontal surfaces (floors and roofs). Calculations of surfaces at each level are done based on priory defined characteristic of the urban district (width and height of streets and buildings as well as the density of built-up structure).

2.1.2. Modelling domain

Defining and setting up new modelling domains (NMD) is an initial, preparatory step to further calculate the climate generation files for chosen domain resolution. Three modeling domains – U15, U05, and U01 (Figure 1), varying in geographical extension and resolution, were created for the project. Domain U15 spans over major part of continental Europe, The British Isles, and Fennoscandia and western part of East European Plain. Domain U05 covers major part of The Great European Plain, easternmost part of United Kingdom, southern part of Scandinavian Peninsula, westernmost part of East European Plain. Domain U01 includes the territory of mainland Denmark, with the Bornholm Island, the northernmost territories of Germany and Poland; and the southernmost territory of Sweden. The Enviro-HIRLAM model U01 domain is mostly oriented on studying influence of different land-use and urbanized areas (e.g. Copenhagen Metropolitan Area) on formation and evolution of meteorological fields within the surface and atmospheric boundary layers.

All domains are constructed in the rotated system of coordinates (RSC). RSC is used to keep the size of domain grid cells almost equal. The selected South Pole latitude (PoLat) is -40 degrees, and the pole longitude (PoLon) is 10 degrees, for all domains. Moreover, for all three domains the south, north, west, and east boundaries are given also in the rotated system of coordinates. The horizontal resolutions are equivalent approximately to: **U15** – ca. 15 x 15 km; 0.15 degree. **U05**: ca. 5 x 5 km; 0.05 degree. **U01**: ca. 1.5 x 1.5 km; 0.015 degree. At highest chosen resolution of about 1.5 km, it is still possible to run hydrostatic model because there are no large changes in terrain/ heights (highest elevation is less than 200 m over the Jutland Peninsula) over Denmark which is in focus. The parameters of the domains extents are given Table 1.

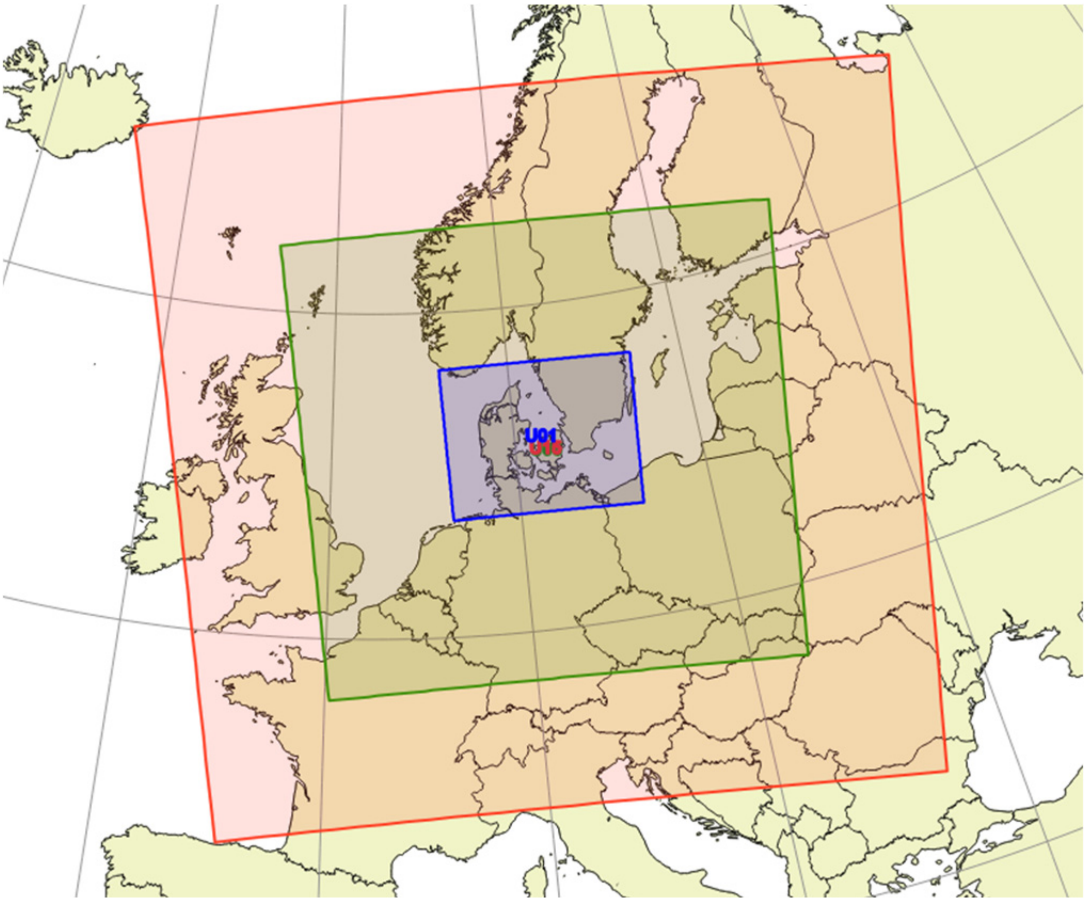

Fig. 1: Enviro-HIRLAM U15 (red), U05 (green), and U01 (blue) domains with resolutions of 0.15, 0.05, and 0.015 [degrees] respectively.

Tab. 1: Enviro-HIRLAM model U15, U05, U01 domains parameters.

Description of parameter	**Parameter**	**U15**	**U05**	**U01**
Horizontal resolution in degrees	RES	0.15	0.05	0.015
Horizontal resolution in km		15	5	1.5
Domain size				
Number of grid points along longitude	NLON	154	298	394
Number of grid points along latitude	NLAT	148	282	310
Number of vertical levels	NLEV	40	40	40
Width of boundary zone	NBNDRY*	10	10	10
Total number of grid points in the domain		22792	84036	122140
Area covered by the domain in km^2		5128200	2100900	274815
Domain boundaries (in RSC)				
South border	SOUTH	-5,505	-1,505	3,670
North border	NORTH	16,545	12,545	8,305
West border	WEST	-10,505	-6,505	-2,089
East border	EAST	12,445	8,345	3,806
Pole latitute	POLAT	-40,0	-40,0	-40,0
Pole longitude	POLON	10,0	10,0	10,0

2.2. Data processing for urban modeling

2.2.1. Land-use datasets

CORINE Land-Cover

Two CORINE datasets for Denmark were used, one for the year 2006 (CORINE 2006), and second the most up-to-date for 2012 (CORINE 2012). CORINE (Coordination of Information on the Environment) is a programme initiated by the European Union (EU) in 1985, aimed at gathering information on environment on certain priority topics for the EU. These topics include e.g. air pollution, natural resources, biodiversity, soils, land-cover, land-use, biotopes etc. CORINE Land-Cover dataset is part of the EU programme and it is a cartographic inventory of 44 classes of different surfaces in Europe. Datasets are available in either vector or raster format in resolutions of 100m or 250m. Both used datasets are freely available. CORINE 2006 dataset can be downloaded through the EEA website (http://www.eea.europa.eu). CORINE 2012, released in November 2014, is at the moment of submitting this work only available through Danish sources (http://www.geodata-info.dk)

Afforestation Areas – Plan DK

Afforestation areas dataset (*Skovrejsningsområder – PlanDK*) is a vector cartographic inventory delineating areas designated for afforestation and areas where afforestation is unwanted. Dataset was prepared by Nature Agency (*Naturstyrelsen*) which is and organization under the Danish Ministry of Environment, and is freely available at (http://geodata info.dk/). Afforestation dataset contains two classes – *Afforestation wanted* and *Afforestation unwanted*. Only Afforestation wanted was used.

2.2.2. Extraction and integration of the datasets

Climate files for three selected modeling domains (see Fig. 1) were generated with Enviro-HIRLAM model. The generated output files can be used in QGIS as raster and contain information on the geographical extent of the domain, latitude and longitude of grid cells, and the fractions of each land-cover classes in the grid cell. All three domains (U15, U05, U01) were constructed in a rotated system of coordinates (RSC). To integrate the data and analyze it in QGIS, these domains were converted into regular system of coordinates (latitude - longitude). In the next step, parameters of converted domains were used to generate a vector grid in QGIS, with the geographical extent of domain U01 and resolution of 1.5 km. This grid is necessary for processing CORINE land-cover data, in the following steps.

2.2.3. Reclassification of land-cover classes

Area of interest for the project was delineated by the extent of the Finger Plan (Figure 2). All changes in land-cover data necessary to were made only for the selected area.
The next step was to combine and reclassify the CORINE and Afforestation Areas datasets using QGIS, to fit requirements of Enviro-HIRLAM model and BEP module (Sattler, 1999).
In the Enviro-HIRLAM model with BEP module included the land surface is represented with 5 tiles: forest, low vegetation, bare soil, ice, water. BEP module replaces bare soil at specified locations with urban tile. Urban tile is further divided into urban districts which represent different urban areas in the metropolitan area. Mahura et al. (2005), proposed reclassification of the relevant CORINE artificial surfaces classes in CPH-MA into three urban districts: High Buildings District (HBD), Industrial Commercial District (ICD), and Residential District (RD). Examples of BEP urban districts in CPH-MA are presented in Figure 3.
Note that Danish CORINE dataset classifies golf courses and summer houses areas as class 1.4.2 *Sport and leisure facilities*. This class is reclassified as RD urban district for the purposes of BEP module. This was modified and only summer houses areas were reclassified as RD urban district.
Relevant CORINE classes and Afforestation Areas class were reclassified into forest tile.
Summary of the dataset reclassification is presented in Table 2.
Reclassified datasets were imported into QGIS and re-projected to EPSG:32632 (WGS84/UTM32N) projection, to ensure datasets overlap. Forest class and urban districts were extracted and saved into separate layers. Each layer was intersected with the U01 domain grid. The result was a set of files (one per land-cover class/district) containing information on the fraction of land-cover class inside each grid cell. It is possible that one grid cell may contain several different classes or urban districts. Modification and recalculation of the land-cover fractions inside grid cells was performed to obtain input files representing each of the scenarios of land-cover change.

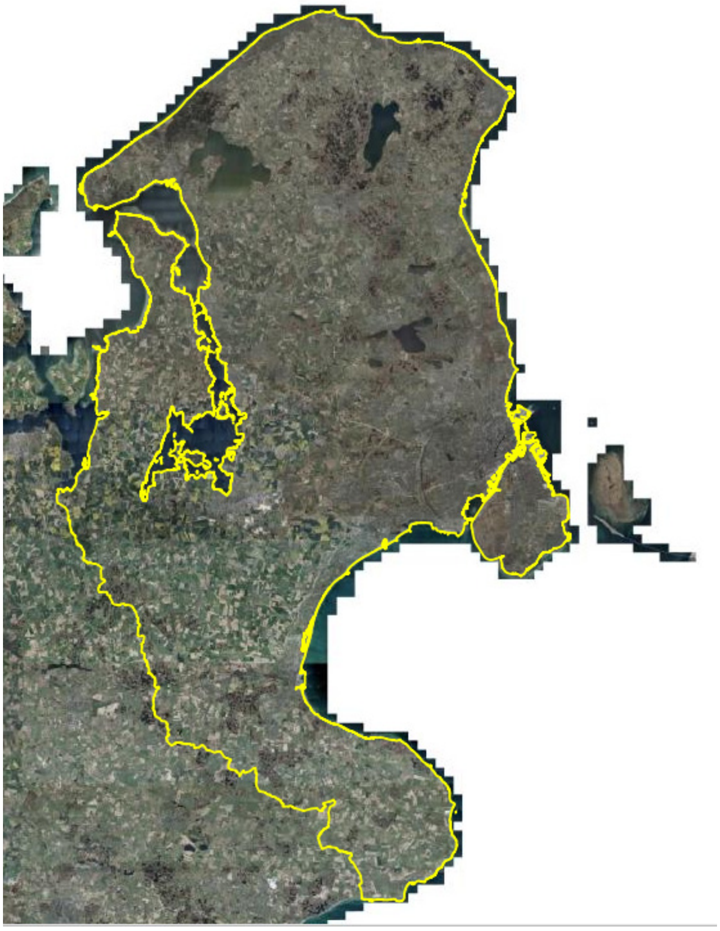

Fig. 2: The extent of the Finger Plan. Northern Zealand, Denmark. © Orthophoto COWI 2012

Tab. 2: Reclassification of the CORINE 2012 and Afforestation Area – Plan DK datasets into Enviro-HIRLAM tiles and BEP module urban districts for Copenhagen Metropolitan Area

CORINE 2012 Land Cover		**Enviro-HIRLAM**	**BEP module**
CORINE Code	**CORINE 2012 class**	**Tile**	**Urban District**
1.1.1	Continuous urban fabric	URBAN	HBD
1.1.2	Discontinuous urban fabric	URBAN	RD
1.4.2 (modified)	Sport and leisure facilities	URBAN	RD
1.2.1	Industrial or commercial units	URBAN	ICD
1.2.2	Road and rail networks and associated land	URBAN	ICD
1.2.3	Port areas	URBAN	ICD
1.2.4	Airports	URBAN	ICD
1.3.1	Mineral extraction sites	URBAN	ICD
1.3.2	Dump sites	URBAN	ICD
1.3.3	Construction sites	URBAN	ICD
1.4.1	Green urban areas	FOREST	
3.1.1	Broad-leaved forest	FOREST	
3.1.2	Coniferous forest	FOREST	
3.1.3	Mixed forest	FOREST	
Afforestation Areas - Plan DK			
	Afforestation wanted	FOREST	

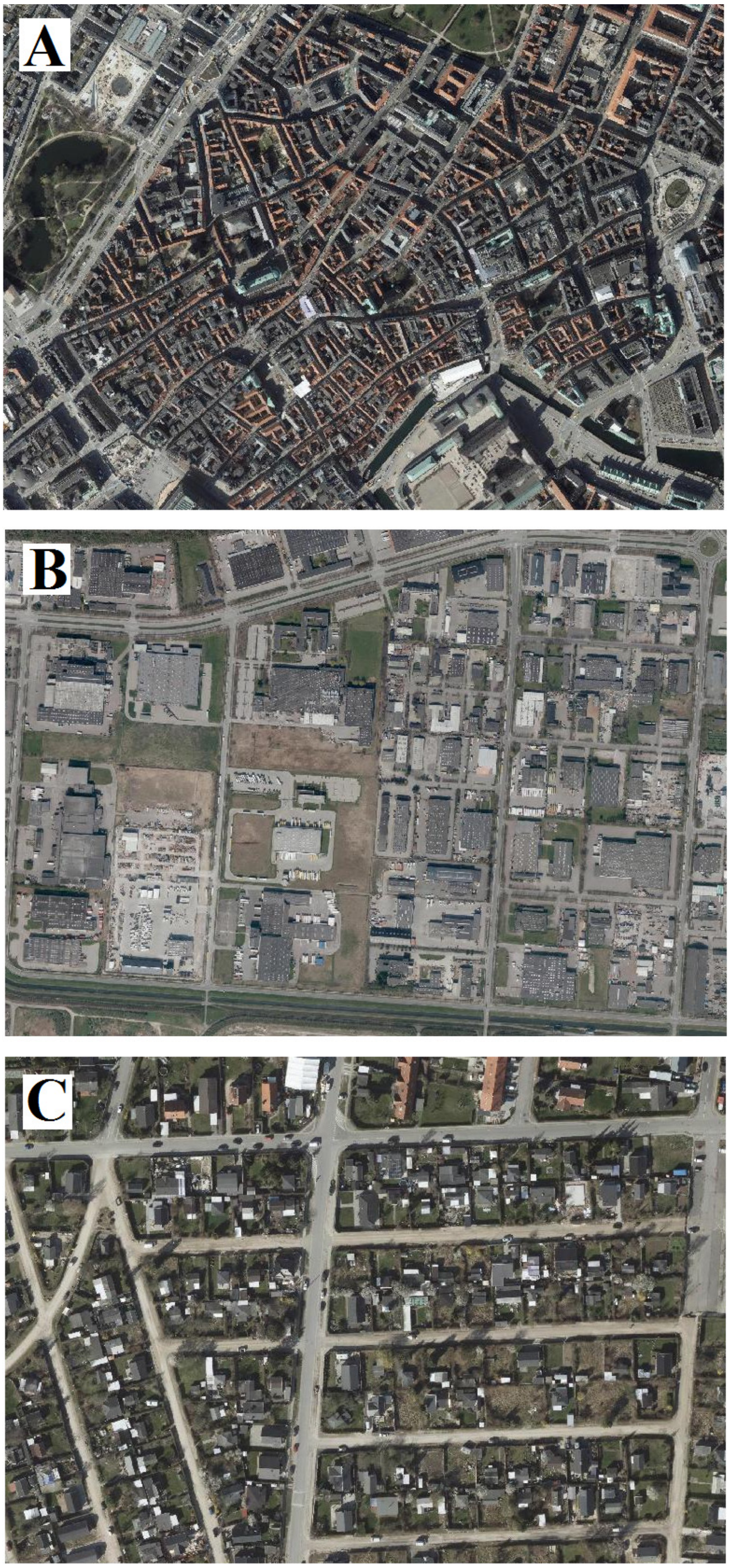

Fig. 3: The urban districts in the Copenhagen Metropolitan Area. A: High Building District (HBD). B: Industrial Commercial District (ICD). C: Residential District (RD). Illustrations extracted from Orthophoto map. © Ortophoto COWI 2012.

2.3. Scenarios

The project investigated the impact of regional forests on formation and development of temperature conditions through series of changes in land-cover scenarios. All the figures presented use the following color code: Red: urban structure. Light green: existing forest. Dark green: new forest area. Blue: water bodies.

Scenario 0: Control (U01)

Control runs from 1st to 5th of July 2009 were performed. These runs do not include urban structure and treat it as bare soils. Hence they do not show the urban impact on the meteorological fields. Note: Control runs are used further to plot the difference in 2Tm fields.

Scenario 1: Baseline (U01 SC1)

First scenario was a simulation of climatic conditions from July 2009 run on an updated CLC 2012 land cover data. Scenario was created to establish a point of reference used to assess the impact scenarios with changed land-cover have on the regional climate (Figure 4).

Scenario 2: Extreme Forest (U01 SC2)

The Extreme Forest scenario, despite its low probability of occurring in reality, was generated to estimate the scale of potential change due to changes in forest cover in the case area extent. Extreme Forest scenario assumes complete afforestation of the case area, with the exception of the already urbanized areas (Figure 5).

Scenario 3: Extreme Urban (U01 SC3)

This scenario, also with low probability, simulates climatic conditions in case of a ‘doubled’ urbanization in the case area. For grid cells that contained urban fractions, these fractions were doubled; maximum possible value of urban fraction in a grid cell was equal 1 (100%). As many grid cells contained more than one type of urban fraction the increase and recalculation was done in a following way: 1) doubling of the HBD fraction, 2) doubling of the ICD fraction, 3) doubling of the RD fraction (Figure 6).

Note: Preparing scenario assuming full urbanization of the entire domain is possible, but the simulation results provide physically unreasonable meteorological patterns.

Scenario 4: Afforestation (U01 SC4)

Danish Forest Act; Planning Act 11a, 11 (Bekendtgørelse af lov om skove, Kortlægning af skovrejsningsområder jf. planloven 11a, 11) dedicates approximately 185 km^2 to afforestation within the extent of the Finger Plan, increasing the existing forest cover by 51%. This scenario estimated possible impact of the increased forest land-cover if the plan was fulfilled following the Planning Act. Afforestation Areas dataset was combined with the CLC2012 dataset, keeping the spatial distribution and sizes of the dedicated new forest areas (Figure 7).

Redistribution scenarios: 5 (U01 SC5) and 6 (U01 SC6)

Two scenarios of potential redistribution of the 185 km^2 of forest dedicated areas were generated. Both scenarios used exactly same area of new afforestation. These two scenarios were generated in order to investigate whether redistribution of the new forest areas can have greater impact on the

T2m fields in CPH-MA than the location of new afforestation as in the Danish Forest Act. These new scenarios focus on ameliorating the climatic conditions in CPH-MA, hence the new forest areas were accumulated in the close vicinity of the Copenhagen center.
It must be noted that Danish Forest Act uses zoning system, to delineate areas where afforestation is wanted/possible or not. This study investigates impact of regional forest on climates and it does not aim at finding the optimal location for new forest areas. Therefore, the zoning system was not considered when redistributing areas for afforestation.

Scenario 5: Ring (U01 SC5)

New forest areas were placed as close to the CPH-MA as possible. New forest filled the ring of 21 km radius away from the center of Copenhagen. New forest filled spaces between urban ‘fingers’ of the FP, and supplemented green wedges, as well as southern part of Amager (Figure 8).

Scenario 6: Wind Dependent (U01 SC6)

This scenario tested the impact of regional afforestation if it was placed accordingly to the dominating wind directions. Therefore, new forest was placed only in W-WS sector from the center of Copenhagen. New forest in this scenario has a 24 km wide front expanding in W-WS sector (Figure 9).

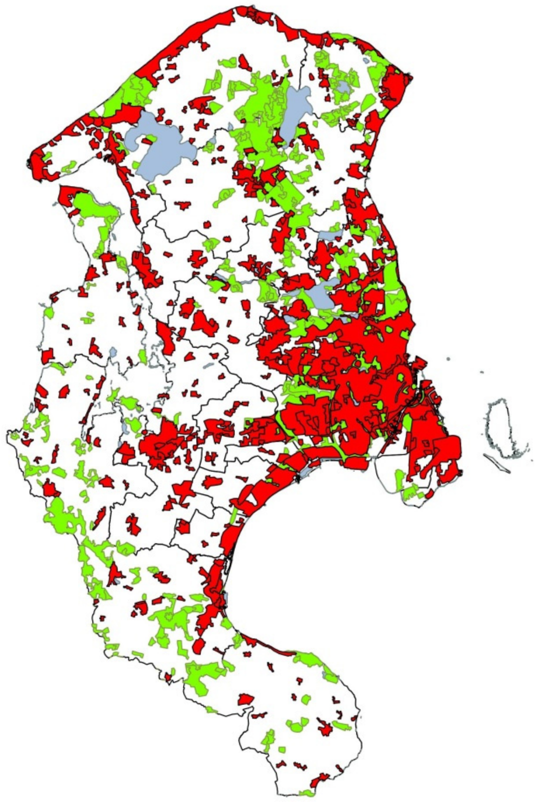

Fig. 4: Spatial representation of the Scenario 1: Baseline.

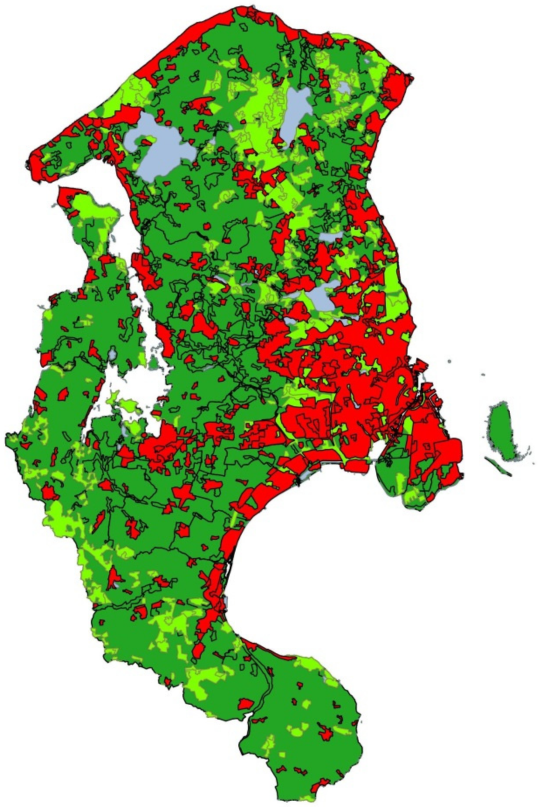

Fig. 5: Spatial representation of the Scenario 2: Extreme Forest.

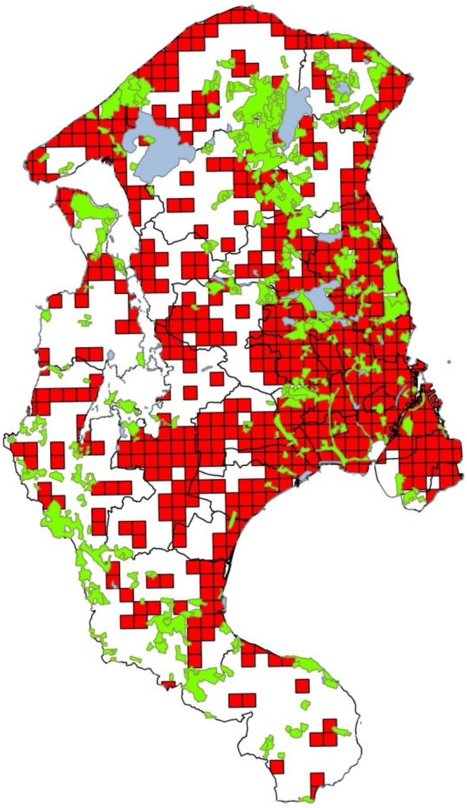

Fig. 6: Spatial representation of the Scenario 3: Extreme Urban.

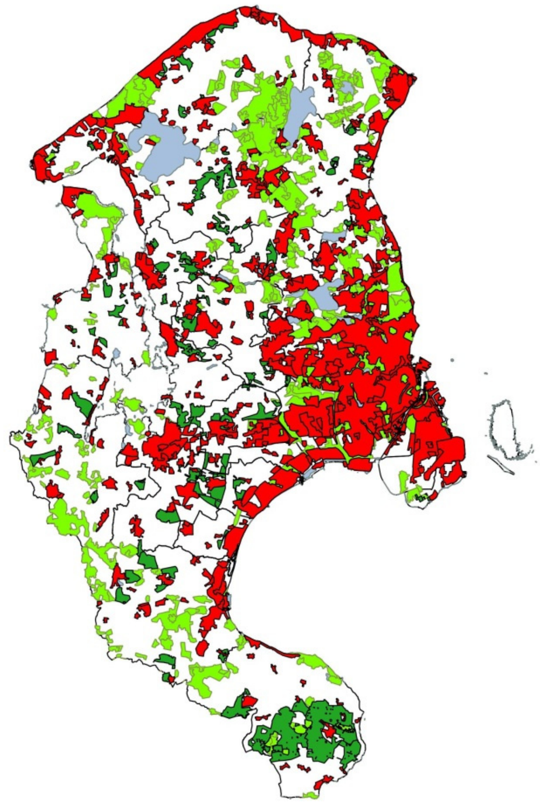

Fig. 7: Spatial representation of the Scenario 4: Afforestation.

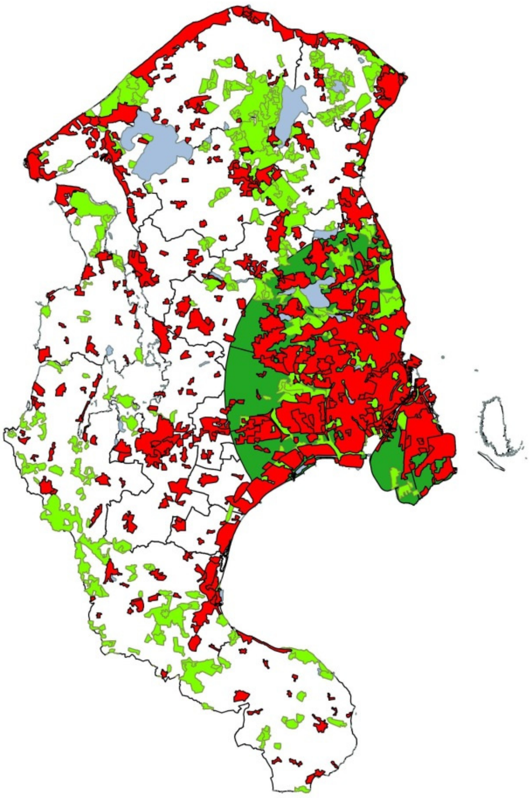

Fig. 8: Spatial representation of the Scenario 5: Ring.

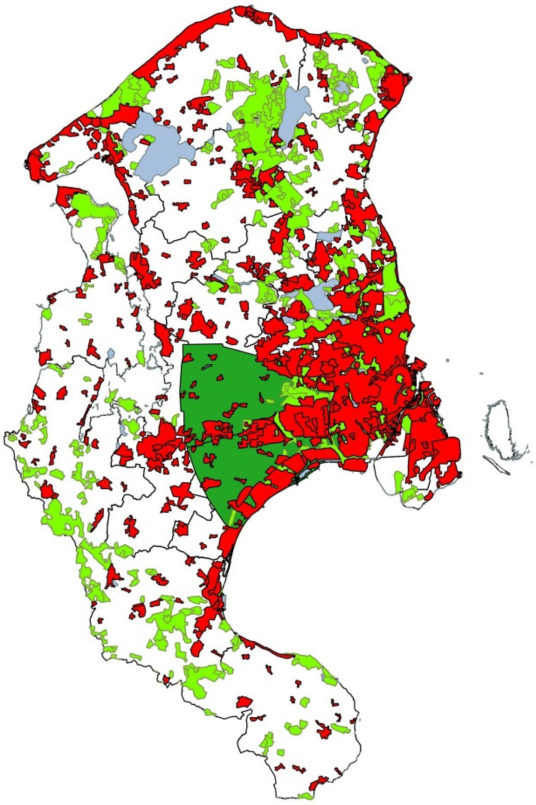

Fig. 9: Spatial representation of the Scenario 6: Wind Dependent.

2.4. Project setup

The project focused on the time period from 1st to 5th of July 2009. July 2009 was selected as it was a relatively warm month (Cappelen, 2010) and was characterized by many days with Low Wind Condition (LWC). The selection of days was based on the criteria of calm conditions during the entire day. LWC days were selected to minimize synoptic scale effects. The influence of the CPH-MA on formation and development of meteorological fields is better visible during the LWC days as mixing of the air masses is lower. The criteria for calm day are: clear sky, low wind speed (below 3 m/s), frequently shifting wind direction, low relative humidity, high atmospheric pressure, and horizontally close to homogenous temperature field (Velazquez-Lozada et al. 2005). The 3rd and 5th of July were LWC days. Simulations were performed for all days, including July 4th which had Typical Wind Condition (TWC).

The Interaction Soil-Biosphere-Atmosphere (ISBA) land surface scheme, originally developed by Noilhan and Planton (1989), was modified by Mahura et al. (2005) to include the urban signature using the BEP module and add simple Anthropogenic Heat Flux (AHF) to the surface scheme. In this study, AHF value was set up to 57 W/m^2, typical for summer conditions in Copenhagen (González-Aparicio et al, 2011). In all scenarios (except Scenario 0: Control) Building Effect Parameterization module (BEP) was included. If BEP module is not included in the simulation urban areas are treated as bare soils, and impact of urban areas on meteorological fields is not visible.

2.5. Analysis approach

Area of interest for the project was delineated by the extent of the Finger Plan (Figure 2). Analyses were performed for the entire selected area or for specified regions.
Three different regions in CPH-MA – urban, suburban, and rural – were selected (Figure 10). These regions were further used to analyze differences in T2m under each scenario. Each region was based on a 6x6 grid cells, with each cell size of 1.5 km, which resulted in a 9x9 km area.
Region 1 – urban, covered the central area of Copenhagen. Region was centered on Vesterbro as it is known to be the warmest area of Copenhagen (Bühler, 2010).
Region 2 – suburban, covered Herlev and its surroundings. This area is a mosaic of urban, agricultural, and forest land-uses.
Region 3 – rural, covered area northward Roskilde, which consisted primarily of agricultural fields and small patches of urban and forest areas.

Fig. 10: Urban (1), suburban (2) and rural (3) regions shown on the orthophoto of Copenhagen Metropolitan Area.

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2.5.1. Types of analysis

Modeling results were analyzed in two different ways, employing METGRAF and QGIS software tools.

Analysis 1: Difference in temperature fields between scenarios and regions

This analysis focused on comparing the modeled difference in T2m regions and scenarios. Difference temperature fields at 2 meters height were plotted using METGRAF tool
To analyze the difference in temperature fields the highest isoline was selected. Plotted results were uploaded into QGIS and overlapped with the grid cells of Regions 1-3. In the next step, through assessment the highest isoline passing each region was identified, for every hour on a diurnal cycle that was modeled. Identified values were then transferred to Microsoft Excel sheet and processed by calculating average and maximum values on a time series.

Analysis 2: Differences in spatial distribution of air temperature fields at 2m height in CPH-MA

This analysis was directed at comparing changes in T2m field structures in the entire extent of the Finger Plan. Contribution of the T2m levels and the overall coverage of temperature fields were assessed.
Plotted results were uploaded into QGIS and georeferenced[1]. In the next step, temperature fields were digitized and T2m ranges were recorded in attribute tables. Areas of digitized T2m fields were calculated in QGIS and percentage changes between the scenarios were estimated. Total difference in temperature fields was calculated for each UTC hour and in details for each temperature interval with 0.25ºC step (e.g. 0.50 – 0.75, 0.75-1.00 etc.).

3. Results and Discussions

3.1. Analysis 1: Difference in air temperature fields between Regions and Scenarios

Differences in T2m on a diurnal cycle were observed between the three selected regions of the CPH-MA, representing urban, suburban and rural for all 6 scenarios for the three days of 3-5 July 2009. Highest isoline was subtracted from the modeled T2m fields for the selected time in the individual regions (Figures 11, 12 and 13). Variability identified for selected scenarios indicates the impact of the urban area on the temperature regimes. The lower the variability the closer it is to the Scenario 0: Control, which assumed no urban areas in the entire domain U01. Table 3 presents averaged difference in T2m fields between regions for different Scenarios.

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[1] Georeferencing - Aligning geographic data to a known coordinate system so it can be viewed, queried, and analyzed with other geographic data. Georeferencing may involve shifting, rotating, scaling, skewing, and in some cases warping, rubber sheeting, or orthorectifying the data. [after: ESRI GIS Dictionary]

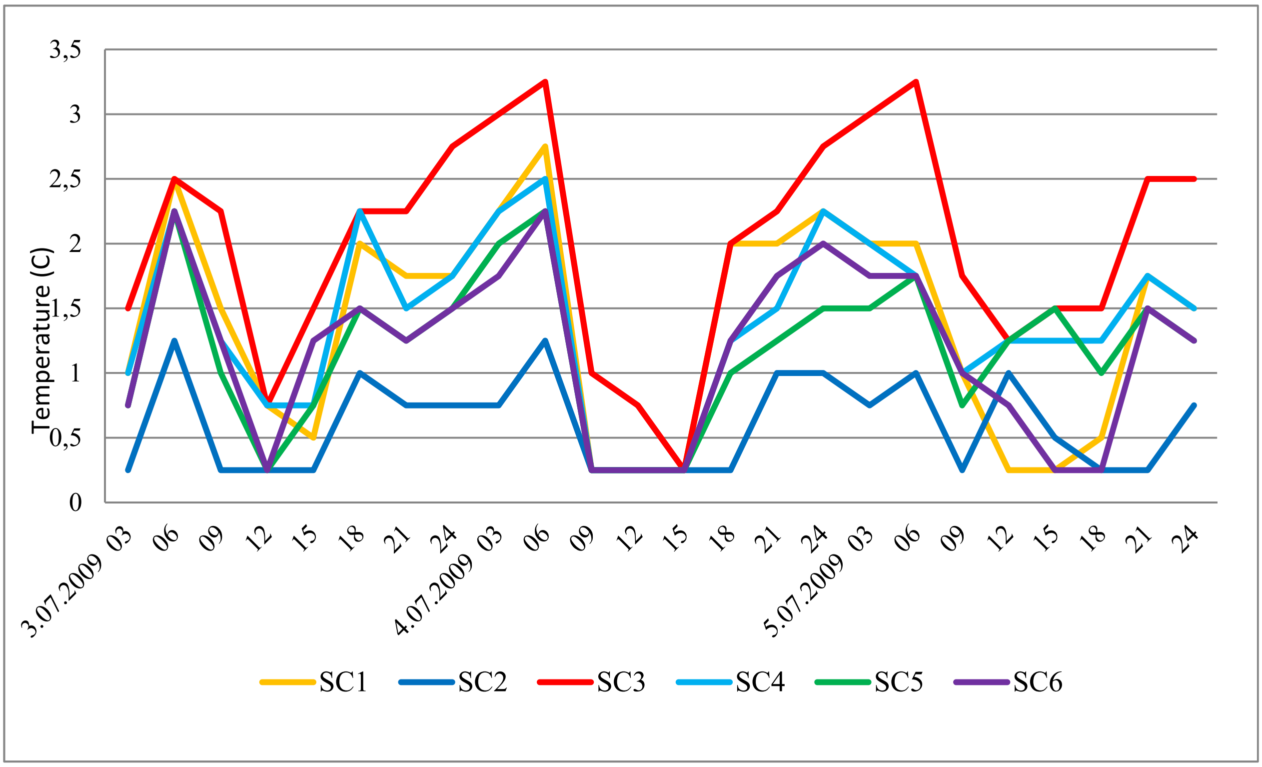

Fig. 11**:** Urban region: Difference in air temperature at 2m (deg. C) between 6 scenarios.

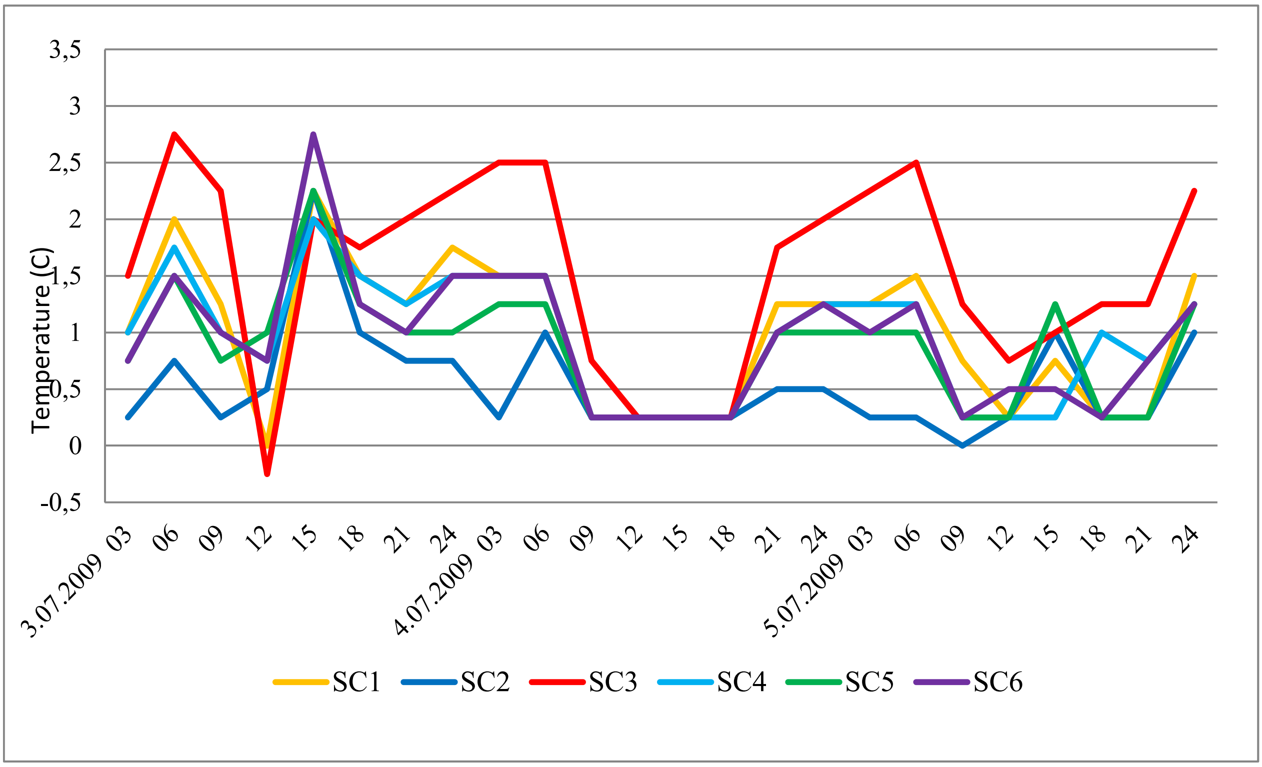

Fig. 12: Suburban region: Difference in air temperature at 2m (deg. C) between 6 scenarios.

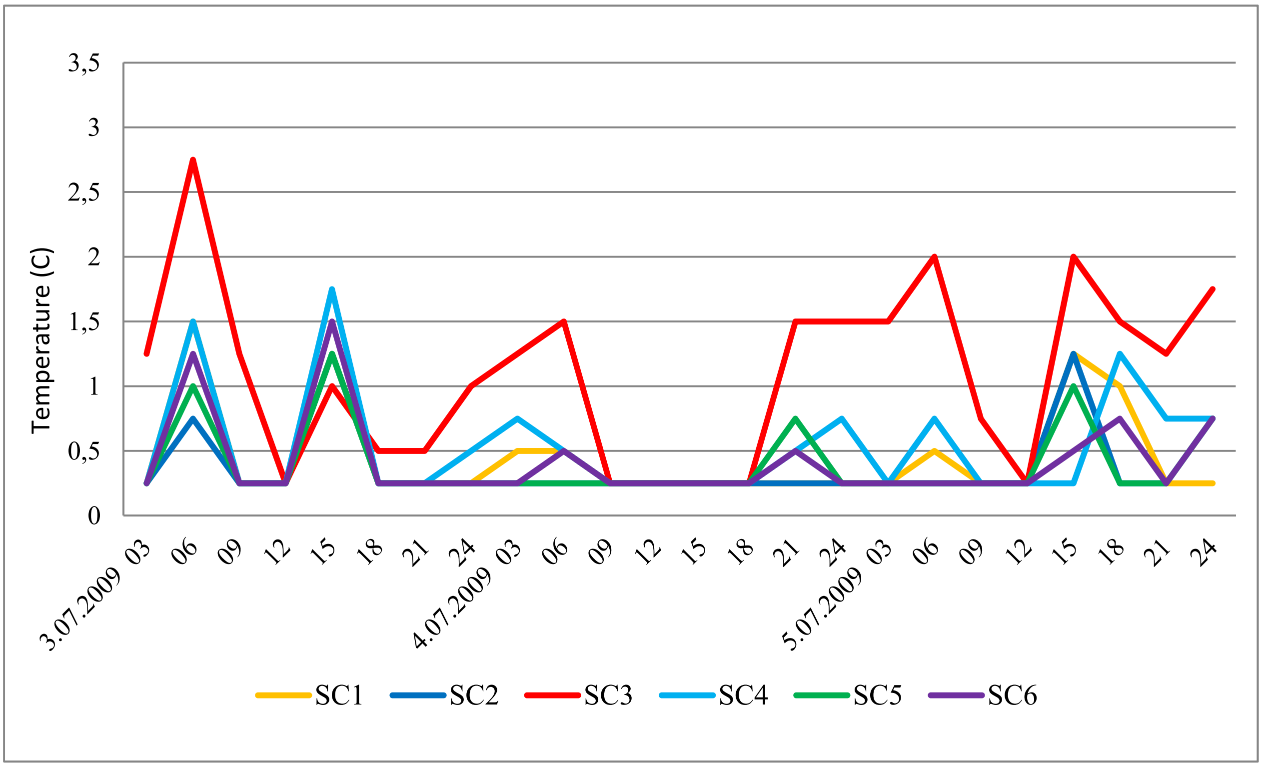

Fig. 13: Rural region: Difference in air temperature at 2m (deg. C) between 6 scenarios.

Tab. 3: Averaged difference in air temperature at 2m (deg. C) fields between regions for different scenarios for 3-5 July 2009.

Scenario	**Difference**	**Region**		
		1 - Urban	**2 - Subrban**	**3 - Rural**
SC1	Highest	2.75	2.25	1.50
	Average	1.40	1.00	0.45
SC2	Highest	1.25	2.25	1.25
	Average	0.60	0.55	0.36
SC3	Highest	3.25	2.75	2.75
	Average	2.01	1.54	1.09
SC4	Highest	2.5	2.00	1.75
	Average	1.40	0.97	0.54
SC5	Highest	2.25	2.25	1.25
	Average	1.19	0.84	0.39
SC6	Highest	2.25	2.75	1.5
	Average	1.18	0.94	0.42

The presented results (in Table 3 and corresponding figures of this section) confirmed that Urban Heat Island effect exists in the Copenhagen Metropolitan Area. Air temperature fields modeled over the period of three days 3-5 July 2009 had characteristics typical for the UHI phenomenon as described in scientific literature (e.g. Oke, 1973, Oke 1981, Oke 1995). Differences in air temperature at 2m on a diurnal cycle were observed for three regions of the metropolitan area, i.e. urban, suburban and rural. It is well documented that Urban Heat Island effect is most significant in the most urbanized areas, e.g. city centers, decreases in the suburban areas, and is the least intensive in rural region (e.g. Oke, 1973, Oke, 1987). This was confirmed by results of all simulation, including the Scenario 1: Baseline (SC1), which is assumed to be closest to the current, real situation in CPH-MA (Tab. 9). The highest differences and variability were identified for the urban Region 1, covering the City of Copenhagen, second highest for the suburban Region 2, and lowest for the rural Region 3. The difference in T2m for SC1 over urban Region reached up to 2.75°C which is similar to values reported in many UHI oriented studies (e.g. Taha, 1997, Wilby, 2003). As seen from the Table and the figures, the influence of urban area is also expanding to the suburban and even rural regions, although there such influence is the smallest on average (about 0.5°C). The effectiveness of each of the scenarios expressed as percentage change in average intensity of air temperature at 2m, compared with SC1 for each of three selected Regions is presented in Table 4.

Tab. 4: Percentage change in the difference of T2m field, compared to Scenario 1: Baseline, for selected region depending on the scenario for the period of July 3-5, 2009. Green: decrease of UHI intensity. Red: Increase of UHI intensity.

Region **Scenario (SC):**	**1 – Urban**	**2 – Subrban**	**3 – Rural**
SC2: Extreme Forest	- 57%	-45%	- 20%
SC3: Extreme Urban	+ 44%	+54%	+ 42%
SC4: Afforestation	< 1%	- 3%	+ 20%
SC5: Ring	- 15%	-16%	- 13%
SC6: Wind Dependent	- 16%	- 6%	- 6%

Despite their low probability the two extreme scenarios, i.e. Scenario 2: Extreme Forest (SC2) and Scenario 3: Extreme Urban (SC3), are worth attention as they indicate the potential maximum impact that changes in land surface may have on the Copenhagen conurbation. These two scenarios indicate what changes might be imposed depending on the planning and policy decisions made for the region.

The SC2, assuming maximum afforestation of the CPH-MA, showed the maximum possible decrease in T2m. The results suggested that forest cover had remarkable influence on decreasing the UHI intensity in the extent of the Finger Plan. For majority of the simulations on the diurnal cycle the urban signature on T2m did not exceed ± 0.5 °C or was significantly low compared to Scenario 1: Baseline (SC1). The intensity of UHI effect in terms of the maximum difference in T2m was lowered by nearly 60%.

The SC3, assuming changes in city structure and overall doubling of the urban area, showed the maximum possible increase in T2m. The results suggested increase in the intensity of the UHI effect in CPH-MA by 42-54%. Moreover, as presented in the following analysis this scenario is linked with great changes in the spatial extent of the UHI effect.

As seen from Table 4, among the afforestation scenarios Scenario 6: Wind Dependent had biggest positive impact on the Region 1 – urban, mitigating the difference in T2m fields by 16% over the period of 3 days. Scenario 5: Ring had the biggest positive impact on the Region 2 – suburban and Region 3 – rural, mitigating the difference in T2m fields by 16% and 13 %, respectively. These results show that two redistribution scenarios – Ring and Wind Dependent have potential to positively enhance temperature conditions in CPH-MA. Although, both scenarios showed very similar impact on urban region, Scenario 5 shows significantly better results in suburban and rural regions. On the contrary Scenario 4: Afforestation, following the Danish Planning Act, has non- or low impact on modifying T2m urban and suburban areas in CPH-MA.

Figure 14 presents the averaged difference in T2m fields for all three regions (urban, suburban, and rural) over period of three days for the four (1, 4, 5, 6) scenarios. Assessment of the four selected scenarios showed that highest impact and decrease in T2m fields occurred in the Scenario 5: Ring. Overall difference in highest temperature up to 0.5ºC and difference averaged over an entire day reaching up to ca. 0.25ºC indicate changes in temperature regimes due to changes in land-cover (also see Tab 3).

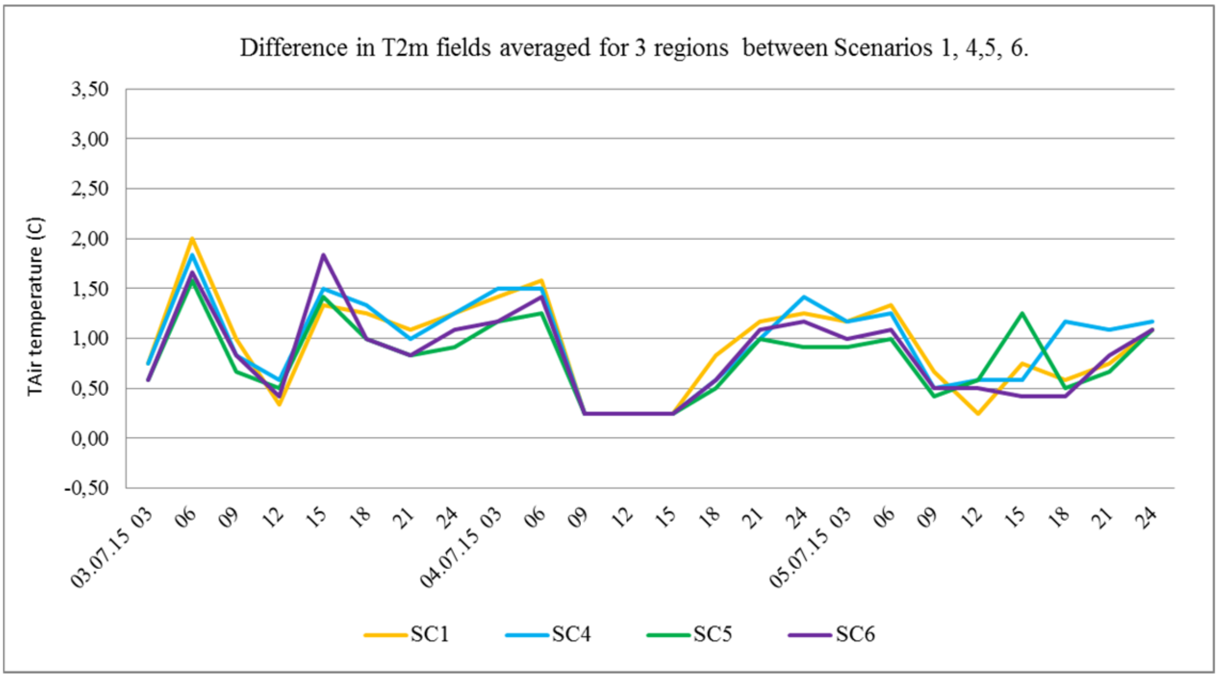

Fig. 14: Difference in T2m fields for averaged for the three selected regions between Scenarios 1: Baseline (reference) and Scenarios 4, 5, and 6, for time period 3-5 July 2009.

These results confirm that increased forest cover can modify the UHI effect in CPH-MA. These results represent the differences in highest values identified in each of the regions. They do not indicate however, the changes in spatial distribution and structure of the T2m fields. That is further addressed in chapter 3.2.

3.2. Analysis 2: Differences in spatial distribution of air temperature fields at 2m height in CPH-MA

3.2.1. Differences in spatial distribution of air temperature fields for the six scenarios

Differences in spatial coverage are assessed on the example of the six selected Scenarios for 3rd of July 2009 06 UTC (Figure 15). That day was characterized by Low Wind Conditions, due to such conditions the impact of CPH-MA on T2m fields expands in all geographical directions and becomes more significant. UHI effect intensifies during LWC conditions. It should be noted that temperature range ± 0.25ºC was excluded from analysis as 'noise'. The results of this analysis indicate significant impact of land-cover changes on the formation and development of T2m fields in CPH-MA. Presented analysis was performed on the example of 03 UTC on 3rd of July 2009, which according to Tab 9 was characterized by highest intensity of the UHI effect for most of the Scenarios.

Highest impact was identified for the Scenario 2: Extreme Forest. The result indicate that in situation of maximum afforestation of the extent of the Finger Plan the UHI effect can be limited almost in the entire CPH-MA, except for the very center of Copenhagen.
The result of the Scenario 3: Extreme Urban, assuming doubling of the urban area and current amount of green areas, suggested radical expansion and intensification of the UHI effect in CPH-MA. Nearly the entire are of interest showed changes in the difference in T2m fields.

All Scenarios assuming varying level of afforestation offer potential to decrease the spatial extent and intensity of the UHI. This analysis further confirmed that the Scenario 5: Ring has the highest potential and impact on modifying urban temperature regimes.

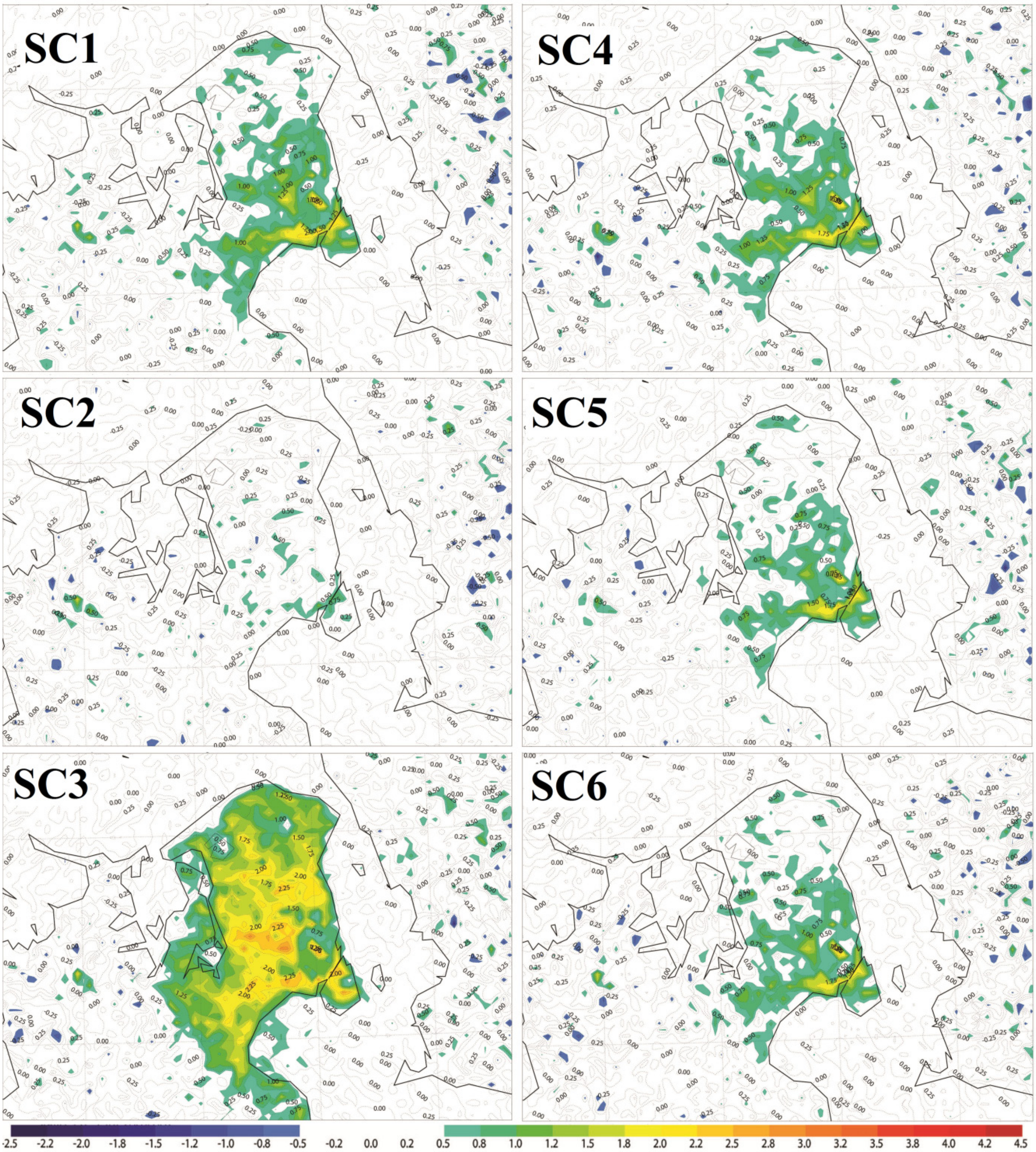

Fig. 15: Difference in air temperature fields at 2m (°C) for 3rd of July 2009 at 06 UTC for 6 selected scenarios: Scenarios 1: Baseline (SC1), Scenario 2: Extreme Forest (SC2), Scenario 3: Extreme

Urban (SC3), Scenario 4: Afforestation (SC4), Scenario 5: Ring (SC5), Scenario 6: Wind Dependent (SC6).

3.2.2. Differences in spatial coverage of air temperature fields for selected scenarios

Relation between spatial structure and coverage of air temperature fields were analyzed. Changes between current situation as expressed by Scenario 1: Baseline, and the redistribution of planned afforestation as expressed by Scenario 5: Ring were assessed for the 3rd of July on a diurnal cycle. Difference in T2m fields between Scenario 1 and 5 at 03 and 09 UTC has been assessed in the example below. These UTC times were selected due to clear and easily noticeable differences in their T2m fields, but these differences occur for all UTCs. It should be noted that temperature range ± 0.25ºC was excluded from analysis as 'noise'.
Detailed results of the rest of analysis for the rest of the diurnal cycle on 3rd of July can be viewed in Table 10.

Changes in T2m field spatial structure: 3rd of July 2009, 03 UTC

In Scenario 1: Baseline the difference in T2m field spans primarily over the Greater Copenhagen Urban area (*Københavns Omegns Storkred*s) (See Figure 16 – A). Differences in T2m ranged from 0.50ºC to 1.00ºC. A major part of the area is covered by the difference field that ranges from 0.50ºC to 0.75ºC. Few, small fields with T2m range of 0.75-1.00 ºC are dispersed around that area. The largest fields were in the central and northern-eastern part. The total area of difference in T2m field was ca. 225 km^{2,} corresponding to the 7.5% of the modeled area (ca. 3000 km^2). Field of temperature range 0.50-0.75ºC was ca. 208 km^2 and field 0.75-1.00ºC occupied 17 km^2.

In Scenario 5: Ring difference in T2m field occurred mainly over western and northern-western part of the City of Copenhagen (See Figure 16 – B). T2m field reaches Glostrup to the west, and areas around Lyngby in the north. Differences in T2m ranged from 0.50ºC to 0.75ºC. The total area of difference in T2m field was ca. 72 km^2, corresponding to the 2.5% of the modeled area (ca. 3000 km^2). Field of temperature range 0.50-0.75ºC was ca. 72 km^2 and field 0.75-1.00ºC did not occur in this scenario.

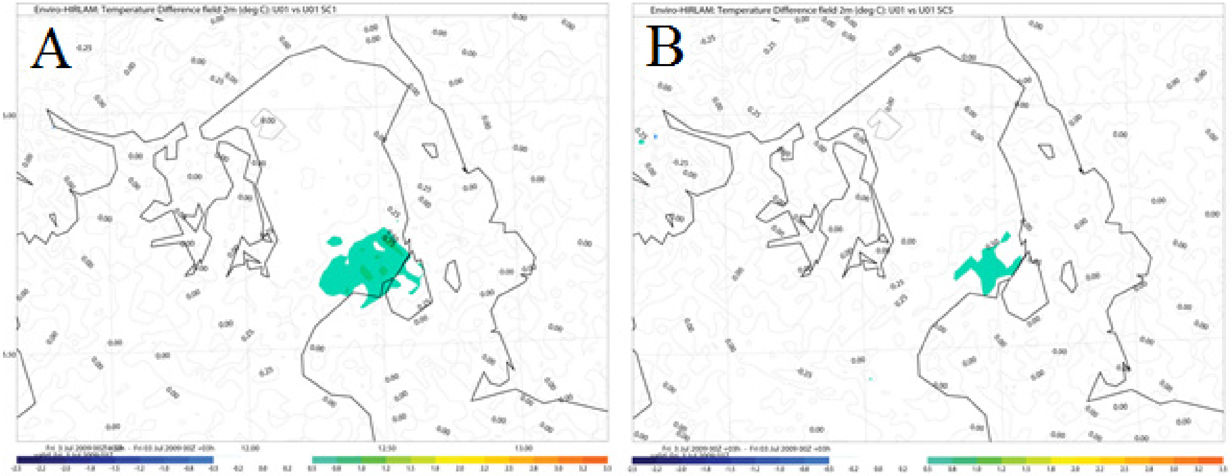

Fig. 16: Difference in air temperature fields spatial structure for Scenarios 1: Baseline (A) and Scenario 5: Ring (B).

Changes in T2m field spatial structure: 3rd of July 2009, 09 UTC

In Scenario 1: Baseline the difference in T2m field spans primarily over the Greater Copenhagen Urban area (*Københavns Omegns Storkred*s), areas around Køge, and extends northward from Greater Copenhagen Urban area (See Figure 17 – C). The difference in T2m ranges from 0.50ºC to 1.50ºC. T2m increases towards the center of the City of Copenhagen. Highest difference occurred over the center of the city and ranged from 1.25ºC to 1.50ºC. Large part of Copenhagen and areas north from the city were covered by the difference field with the range from 1.00ºC to 1.25ºC. This area was surrounded by smaller strip of T2m field ranging from 0.75 to 1.00 ºC. Rest of the difference field had the range from 0.50 to 0.75ºC and spanned over the outer part of Copenhagen, Amager and areas close to Køge. The total area of difference in T2m field was ca. 275 km^2, corresponding to the 9% of the modeled area. Field of temperature range 0.50-0.75ºC was ca. 150 km^2; field 0.75-1.00ºC occupied 58 km^2; field 1.00-1.25ºC occupied 55 km^2; field 1.25-1.50ºC occupied 12 km^2.

In Scenario 5: Ring difference in T2m field occurred mainly over the City of Copenhagen and extended northward from the City to Lyngby and Søborg (See Figure 17 – D). Difference in T2m fields ranged from 0.50ºC to 1.00ºC. The total area of difference in T2m field was ca. 142 km^2, corresponding to the 5% of the modeled area. Field of temperature range 0.50-0.75ºC was ca. 105 km^2, and field 0.75-1.00ºC was ca. 36 km^2. Fields 1.00-1.25ºC and 1.25-1.50ºC did not occur in this scenario.

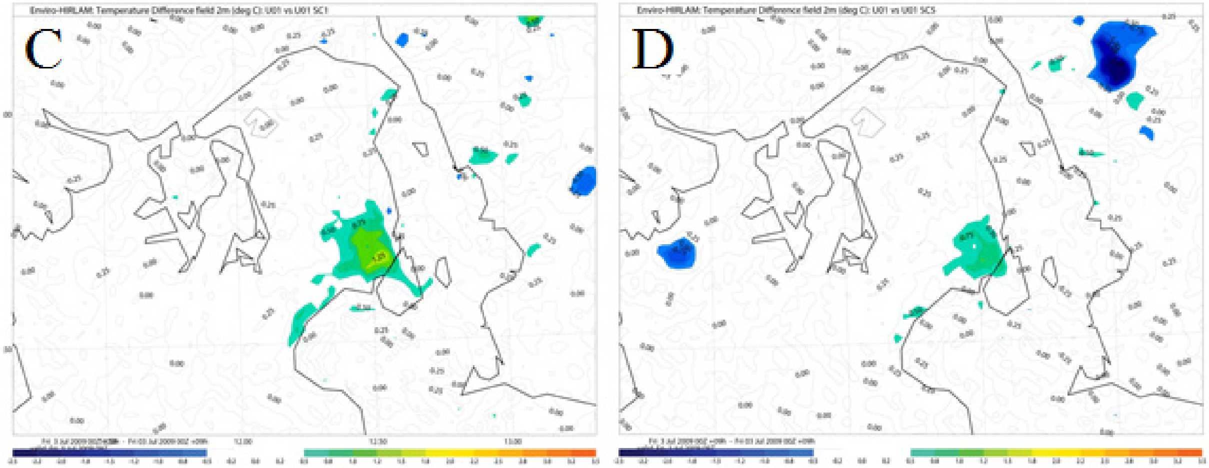

Fig. 17: Difference in air temperature fields spatial structure for Scenarios 1: Baseline (C) and Scenario 5: Ring (D) for 3rd of July 2009, 09 UTC

The presented results further confirm significant decrease in the extent of the UHI effect due to changes in forest cover in CPH-MA. The important aspect of this analysis is that it allows tracking changes in UHI effect spatial extent and coverage. The average decrease in the total area of T2m fields (difference +0.50ºC or higher) on a diurnal cycle for 3rd of July was 40%. Depending on the hour of the day the differences varied from 24% to 68% (See Appendix 1)

4. Discussion and Conclusions

The project sought to answer the hypothesis if well-positioned and well-sized regional afforestation can mitigate the effects of the warming climate and enhance urban living conditions.

To achieve that objective high resolution (1.5x1.5 km) short-term runs for specific dates (3-5 July 2009) with variable wind conditions (LWC or TWC) were performed for the Copenhagen Metropolitan Area (CPH-MA). Separate Enviro-HIRLAM model simulations were done for each of the land-cover change scenarios generated with the presented methodology. Impact of regional afforestation on formation of the meteorological field for the air temperature at 2m in the CPH-MA was estimated. The impact of the forest was studied by evaluating the difference between outputs of the control runs vs. afforestation-urbanized runs for 6 selected scenarios.

The modeling work presented in this study for the six selected scenarios confirmed the project hypothesis. Results indicated that regional afforestation and changes in land-cover can have significant influence on modifying temperature regimes in CPH-MA. All afforestation scenarios indicated a decrease in air temperature fields at 2m height, and reduction in the spatial distribution and intensity of the UHI effect. Results indicated also that planting new forests in CPH-MA area can be most beneficial in urban and suburban areas. Vegetation has the potential to regulate and enhance the urban climate. To explain the rationale for this, one could draw from the results of this work.

The modeling results confirmed that Urban Heat Island effect exists in the Copenhagen Metropolitan Area. This finding is vital as UHI effect is not high on the agenda of the City of Copenhagen (Bühler et al., 2010). Despite the low sense of urgency in combating this climate change related risk effort should be put in minimizing Urban Heat Island effect in metropolitan areas (Runhaar et al., 2012). City of Copenhagen addresses urban heat in its climate adaptation plan (København Kommune, 2011). Plan recognizes rising temperatures as a potential health risks related with it, such as heat strokes, dehydration, and citizens' lower thermal comfort. Moreover, vegetation, and its cooling effect, is suggested as possible tool to address the issue. However, there is lack of formal legislation that would regulate use of green infrastructure in the city (Stysiak, 2014) Moreover, most of the City budget is dedicated to project related with storm water management and even the project planned in 2011 were not realized until today. The project can serve as evidence that UHI is a real issue and should be taken seriously and properly addressed in municipal adaptation strategy.

Combined analysis of air temperature 2m fields intensity, structure and spatial distribution confirmed that regional afforestation can be an important tool in reducing and mitigating rising urban temperatures.

The highest impact on differences in T2m fields, as well as the spatial distribution and structure of UHI effect, was identified in the two extreme Scenarios, i.e. Extreme Forest and Extreme Urban. These scenarios, despite their low probability, are valuable in estimating what changes might occur in CPH-MA depending on the planning and development strategies implemented in the area. The Extreme Forest Scenario indicated lower intensity of UHI effect up to 1.5°C (decrease nearly 60%) in the difference in T2m fields. These findings are similar to those suggested by Gálos et al. (2011) who reported 1°C change in temperatures in hypothetical study assuming afforestation of entire area of Hungary. What is more, in majority of simulations the urban signature on T2m did not exceed ± 0.5°C. In some of them, the difference in temperature fields was visible but significantly lower in intensity compared to current situation in CPH-MA, modeled with Scenario 1: Baseline. In these cases also the spatial extent of the T2m fields was greatly reduced. Nevertheless, this finding also indicated that rising temperatures cannot be fully compensated even in this hypothetical Scenario assuming maximum afforestation of CPH-MA.
The results of Extreme Urban scenario suggested the increase in T2m fields' intensity by additional 0.5°C. However, this value alone does not show the magnitude of change following the suggested increase in urban areas. Results of Analysis 2 clearly identified radical increase in the spatial extent and intensity of the UHI effect in CPH-MA. This Scenario clearly shows the negative result of potential, rapid urban sprawl, if it not properly balanced with the planning and establishment of new green areas that would help to mitigate the likely increase in UHI effect. These results comply with those suggested by Gill et al (2007) that increase in surface temperatures in Greater Manchester are can be affiliated with changing the ratio between built-up and vegetative areas.

From urban planning perspective these findings highlight the need for balancing the new urban development projects with new green areas. This is crucial in terms of securing urban population thermal comfort. Warming climate gradually increases the danger of health heat-related risks.
Spatial differences in the effect of afforestation have been assessed for the selected Scenarios. All three afforestation scenarios, i.e. Scenario 4, 5, and 6, indicated some level of change in UHI intensity. Firstly, it results showed that afforestation suggested in Scenario 4: Afforestation, assuming increase in forest cover in small patches dispersed over the entire extent of the Finger Plan, has no- or low impact on mitigating UHI effect. Two redistribution scenarios showed relatively higher influence on temperature regimes. The spatial allocation of new forest in Scenarios 5 and 6 was more localized and accumulated in specific areas of CPH-MA. These findings suggest that planning afforestation in form of large, continuous forest located close to the metropolitan area has can be more beneficial in modifying urban climate than collection of small, scattered forest patches. Similar results were presented by (Stülpnagel et al., 1990) from Berlin study of large parks areas. It was suggested that largest parks such as Tergarten (212 h) has much higher influence on air temperatures than smaller parks. However, it must be noted that difference between Scenario 5 and 6 were also found, although they both assumed allocation of a new forest in one, large area. Scenario 5: Ring showed potential to mitigate differences in T2m by up to 0.25°C. It was also assessed that Scenario 5 offers better potential in reducing the spatial extent of the temperature fields. This finding suggests that planning of many large patched of new forest between already existing urban areas can be more beneficial than creating one, huge forest area.

Warming of the climate is not considered in the Danish afforestation efforts. However, taking into consideration the scale, time and resources put into this programme climate change adaptation should be a bigger part of it. Even though negative effects of the warming climate can take more time to manifest themselves in Denmark than in other European countries, the necessary preparatory steps should be taken soon. Especially, when taking into account time needed for the newly established forests to have impact on local and regional climate.
More research focusing on the relation of land-cover and land-use, and formation and development of meteorological fields is needed to identify the areas where forest cover increase might be the most effective from the climatic point of view. Regional scale information is essential for the development of future forest and land-use policies.

Project considerations

Scope of the project

The project focused on relation between regional forest and temperature regimes in the metropolitan area of Copenhagen. However, biosphere-atmosphere feedbacks are not linear. Changes in land-cover and land-use lead to shifts in formation and development of all meteorological fields and patterns: temperature regime, relative humidity, wind characteristics (speed and direction), precipitation, chemicals species transport. Changes in these parameters and their potential impact on air temperature fields were not estimated. This could be addressed in future studies. Moreover, this study could be a point of departure to study influence of regional afforestation on changes in, e.g. air pollution (ozone concentrations), precipitation patterns, wind speeds. More case-specific research considering atmosphere-built environment interactions would be a good starting point for development of new strategic policies for metropolitan areas.

Enviro-HIRLAM model limitations

Meteorology-chemistry Enviro-HIRLAM model was used to simulate the impact of selected scenarios of land-cover change on temperature regime in the selected case area. Currently, the highest resolution available in this model is 1.5 km. Such resolution is considered very high for the

needs of majority of meteorological research. When applied urban planning research this resolution allowed obtaining satisfying results at the metropolitan/regional scale. However, 1.5 km resolution would not allow precise studies of climatic conditions at the local scale of individual city. Future studies aiming at researching CPH-MA urban climates at high resolution could employ Large Eddy Simulations (LES) modeling approach which allows performing simulations at a very high, more detailed scale as presented by Mahura et al. (2005) on the example of Copenhagen. Important consideration however, is the different computational time required to perform the runs at different horizontal resolution and time step. LES simulations are due to high resolution and possible time step of ca. 10-15 min. relatively expensive and require more research time. Performing presented study with Enviro-HIRLAM model was relatively cheap and for this type of research at regional scale Enviro-HIRLAM seems to be suitable.
The Enviro-HIRLAM model used in this study was run in hydrostatic mode. The use of hydrostatic mode at selected high resolution of about 1.5 km is still applicable because a relatively flat (highest altitude of less than 200 m asl) terrain of Denmark's modelling domain as well as small scale eddies are barely developing at such resolution and terrain conditions. Moreover, the multi-year verification results shows good level performance for the operational HIRLAM-SKA model (which is basis NWP model of the Enviro-HIRLAM system) running at comparable resolution of 2+ km. Hence, these should not have impact on the project findings and conclusions.

Compatibility of the Enviro-HIRLAM and QGIS

Output files generated with the Enviro-HIRLAM model are written in the GRIB format (GRIdded Binary) which is commonly used operationally worldwide by majority of meteorological centers for numerical weather prediction outputs (NWP). This format is not directly supported by any GIS software. Several steps, including use of meteorological METGRAF software are necessary to integrate results of NWP model into GIS. More research on development of automatic- or semi-automatic and direct way of combining outputs of NWP models and GIS systems is necessary. This would create the opportunity to analyze meteorological data in a more precise and spatially oriented way, as well as making it more accessible for landscape architects and urban designers, to be used in development plans and strategies.

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List of Figures and Tables

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Appendices

App. 1: Changes in T2m spatial structure and area in selected case area on July 3rd 2009.

03.07.2009 Time (UTC)	DIFF T2m range (deg C)	Scenario 1: Baseline		Scenario 5: Ring		Total % change
		Area [km2]	Part of the total area	Area [km2]	Part of the total area	
03	0.50-0.75	208	92%	72	100%	-65%
	0.75-1.00	17	8%	0	0%	-100%
	SUM	**225**		**72**		**-68%**
06	0.50-0.75	586	49%	499	61%	-15%
	0.75-1.00	315	26%	189	23%	-40%
	1.00-1.25	150	13%	82	10%	-45%
	1.25-1.50	68	6%	26	3%	-61%
	1.50-1.75	30	3%	16	2%	-46%
	1.75-2.00	32	3%	9	1%	-71%
	2.00-2.25	11	1%	0	0%	-97%
	2.25-2.50	1	0%	0	0%	-100%
	SUM	**1193**		**823**		**-31%**
09	0.50-0.75	150	54%	105	74%	-30%
	0.75-1.00	58	21%	36	26%	-38%
	1.00-1.25	55	20%	0	0%	-100%
	1.25-1.50	12	4%	0	0%	-100%
	SUM	**275**		**142**		**-49%**
12	0.50-0.75	59	68%	41	62%	-30%
	0.75-1.00	19	22%	16	24%	-17%
	1.00-1.25	8	9%	9	13%	13%
	1.25-1.50	1	1%	1	1%	-54%
	SUM	**87**		**66**		**-24%**
15	0.50-0.75	289	34%	162	29%	-44%
	0.75-1.00	186	22%	119	21%	-36%
	1.00-1.25	109	13%	100	18%	-9%
	1.25-1.50	73	9%	67	12%	-8%
	1.50-1.75	61	7%	57	10%	-6%
	1.75-2.00	44	5%	33	6%	-25%
	2.00-2.25	27	3%	12	2%	-56%
	2.25-2.50	19	2%	4	1%	-78%
	2.50-2.75	19	2%	1	0%	-95%
	2.75-3.00	12	1%	0	0%	-100%
	3.00-3.25	1	0%	0	0%	-100%
	SUM	**840**		**555**		**-34%**
18	0.50-0.75	303	56%	197	52%	-35%
	0.75-1.00	165	30%	133	35%	-20%
	1.00-1.25	38	7%	34	9%	-11%
	1.25-1.50	21	4%	13	3%	-38%
	1.50-1.75	12	2%	1	0%	-94%
	1.75-2.00	4	1%	0	0%	-100%
	SUM	**543**		**377**		**-31%**
21	0.50-0.75	186	51%	166	76%	-11%
	0.75-1.00	124	34%	47	21%	-62%
	1.00-1.25	32	9%	7	3%	-79%
	1.25-1.50	15	4%	0	0%	-100%
	1.50-1.75	9	2%	0	0%	-100%
	1.75-2.00	1	0%	0	0%	-100%
	SUM	**367**		**220**		**-40%**
24	0.50-0.75	235	43%	190	65%	-19%
	0.75-1.00	174	32%	68	24%	-61%
	1.00-1.25	72	13%	31	11%	-58%
	1.25-1.50	46	8%	1	0%	-97%
	1.50-1.75	12	2%	0	0%	-100%
	1.75-2.00	1	0%	0	0%	-100%
	SUM	**541**		**290**		**-46%**