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Impacts of town characteristics on the changing urban climate in Vantaa

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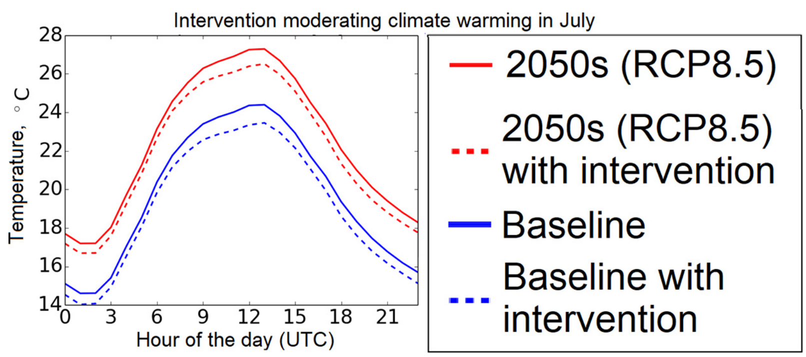
HIGHLIGHTS

- Altering urban characteristics has a climatic impact even in a sparsely built city.
- The share of green spaces and suburban-type land use was increased in simulations.
- The intervention cools the town and the local climate becomes more humid and windy.
- Global climate change dominates over the intervention, except for wind.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, the climatic impacts of modifying urban surface characteristics are examined for the medium-sized city of Vantaa, Finland, in the current climate and in a projected future climate of 2040–2069. In simulations with the SURFEX air-surface interaction model with a horizontal resolution of 500 m, the fraction of green spaces and relatively sparsely built suburban-type land use was increased at the expense of more densely built commercial and industrial areas. The influence of this land use intervention was found to be rather modest but comparable to the effects of the expected climate change under the RCP8.5 greenhouse gas scenario. For temperature, the climate change is the dominating effect, while wind speed is mainly controlled by surface characteristics. For relative humidity, climate change and the imposed intervention are of comparable importance. The results of this sensitivity study are intended to support policy makers by assessing the potential impact of altering the urban layout in order to improve thermal comfort or as a countermeasure to climate warming in a high-latitude city.

1. Introduction

The presence of built environment strongly modifies the local climate (Oke et al., 2017). Nowadays, approximately 50% of the world's population and a large fraction of economic activities reside in the urban environment. Because of the dependence of air quality on

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meteorological conditions (e.g., wind speed and direction, mixing height, air temperature and solar radiation), and because of the strong interlinkages between air quality and climate change (e.g., Fiore et al., 2015), current research is more and more focusing on the study of climate in built-up areas.

Green infrastructure is becoming ever more widely used method of controlling urban climate and air quality and adapting to climate change (Pugh et al., 2012). Local climate change adaptation plans around the world list green infrastructure as a tool for both storm-water management, attenuation of the urban heat-island effect and improving air quality; for instance in the adaptation plans of Copenhagen (Rømø, 2015).

Town characteristics influence urban climate through various air-surface interactions. Several numerical, physically-based surface models are designed to simulate air-surface interactions at a horizontal scale of about 100 m. Examples of such models include CLASS (Verseghy, 1991), CLM (Lawrence et al., 2011), JULES (Best et al., 2011; Clark et al., 2011), LIS (Kumar et al., 2006), Noah (Ek et al., 2003), ORCHIDEE (Krinner et al., 2005), TESSEL (Balsamo et al., 2009), SUEWS (Järvi et al., 2011) and SURFEX (Masson et al., 2013a). Such models can be used either in a standalone mode or coupled to an atmospheric model.

In climate simulation models and numerical weather prediction models, the heterogeneity of the surface is frequently addressed by using a tiling approach, where several surface types may be present in a given grid box (e.g. Masson et al., 2013a). In a tiling scheme, all the surface types within a given grid cell experience the same atmospheric conditions, "forcing", but react individually, according to their respective physical properties. Finally, fluxes representing all the different tiles are aggregated, so that the atmosphere reacts to one representative value for the entire grid-cell.

In many climate models, because of computational expenses, urban parameterizations still follow highly simplified approaches (Masson, 2006). The most common way is to use a vegetation–atmosphere transfer model whose parameters can be modified. Cities are modelled as bare soil or a concrete plate, often using a large roughness length (one to a few meters; Wieringa, 1993; Petersen, 1997).

More advanced parameterization schemes address the complexity of the urban surface through a canyon approach, in which the urban surface is treated as an array of different facets, and the energy budget equation is solved individually for each facet. For example, the models of Masson (2000), Martilli (2002) and Kondo et al. (2005) consider three separate facets of roofs, walls, and road surfaces, while Best et al. (2006), Dupont and Mestayer (2006) and Porson et al. (2009) chose to merge the walls and road surfaces into one single effective canyon, thus considering only two energy budgets.

Such urban canyon type models simulate surface heat fluxes more accurately than the modified-vegetation models. A review and intercomparison of urban models is available in Grimmond et al. (2010, 2011). When focusing on the impact of the built-up environment on the population in cities (in buildings or on the road) or economics (e.g., energy consumption in buildings), it becomes necessary to make a clear separation between buildings, air within urban canyons, roads surfaces, trees, gardens etc. The Town Energy Balance (TEB) model (Masson, 2000; Lemonsu et al., 2004), included in the surface interaction model SURFEX, is an example of a model capable of making this distinction and taking into account a multitude of physical processes.

Many studies have applied physically-based modelling of the built-up environment to study the impact of various urban planning measures aimed at improving thermal comfort and air quality, or reducing energy consumption of buildings in cities (Masson et al., 2013b; Falasca et al., 2019; Taleghani et al., 2019; Chen et al., 2018). Understandably, a majority of these studies have focused on regions and cities suffering from severe heat waves, while cooler regions have received less attention. Yet, heat waves affect the well-being of people and cause premature deaths also in high latitudes (Ruuhela et al., 2018) and the problem is expected to get worse as a result of the on-going global warming. In this study, we use the SURFEX module, including TEB, to explore the climatic impacts of altering urban characteristics in the medium-sized city of Vantaa (>200,000 residents) in southern Finland (60.29°N, 25.04°E). Vantaa belongs to the boreal climate zone (Df according to the Köppen climate classification) and has a seasonal snow cover on average from late December to early April. It can be classified as a decentralized city with no dominant core and no clear distinction between open spaces and built-up areas (Gharbia et al., 2018). Over 60% of the area of the city currently consists of green spaces and water bodies, and only 18% of sealed air-and watertight ground surface (Gharbia et al., 2018). In contrast to southern and Western Europe, more pronounced changes in climate are expected to occur in Finland in winter, rather than in summer (Ruosteenoja et al., 2016).

In order to assess the impact of surface characteristics on local climate, the intervention studied in Vantaa consisted of increasing the share of green spaces. Relatively densely built commercial and industrial areas in Vantaa (and its neighbouring cities Helsinki and Espoo) were replaced by a suburban-type land use featuring lower and less dense buildings and more widespread vegetated areas. The consequences of the intervention were studied with SURFEX both in the current climate and in a projected future climate in the 2050s (an illustration in Fig. 1). Accordingly, we considered four different scenarios: 1) current climate without the intervention, 2) current climate with the intervention, 3) mid-century climate without the intervention and 4) mid-century climate with the intervention. To obtain a measure of the urban heat-island effect, meteorological conditions at the commercial center of Vantaa, Tikkurila, are compared with conditions in the forested area of Sipoonkorpi National Park, which is located at a comparable distance from the coast.

This study is a model-based sensitivity experiment, aimed to assess the response of urban meteorological conditions to increases in the share of green spaces and reductions in building height and fractions of densely built areas. The hypothesis is that the intervention of altering urban characteristics affect local urban climate notably even in a sparsely built city like Vantaa and that for some meteorological variables the magnitude of the response might be even comparable to the projected climatic changes due to the enhanced greenhouse gas effect.

2. Materials and methods

2.1. SURFEX module and the intervention

The impacts of altering urban characteristics in the city of Vantaa on local meteorological conditions in the present and projected future climate were studied by using the regional scale surface interaction module SURFEX (Masson et al., 2013a). As briefly mentioned in Section 1, the Town Energy Balance (TEB) model (Masson, 2000; Lemonsu et al., 2004), included in SURFEX, is a model capable of separating buildings, air within urban canyons, roads, and, if present, trees, gardens etc. This is crucial, since the interactions of the atmosphere with the Earth's surface via the fluxes of heat, momentum and various species depend on the underlying surface.

In more detail, a multitude of physical processes is taken into account in TEB: 1) shortwave and longwave trapping effect of the canyon geometry; 2) anthropogenic sensible heat flux from heated or cooled buildings or from traffic and industry; 3) water and snow interception by roofs and roads; 4) heat conduction and heat storage in buildings and roads; and 5) interactions between the built surfaces and the canyon air (temperature, specific humidity, wind, turbulence).

In this study, SURFEX was deployed over a roughly square domain, having a size of 38 × 42 km, situated on the southern coast of Finland, with the city of Vantaa in the middle (Fig. 2). The applied grid spacing was 500 m by 500 m. The urban land use types over the domain included commercial and industrial areas, airports and ports, parks and sport facilities and suburban types. The characteristics of the city-block and the presence and properties of gardens and parks were

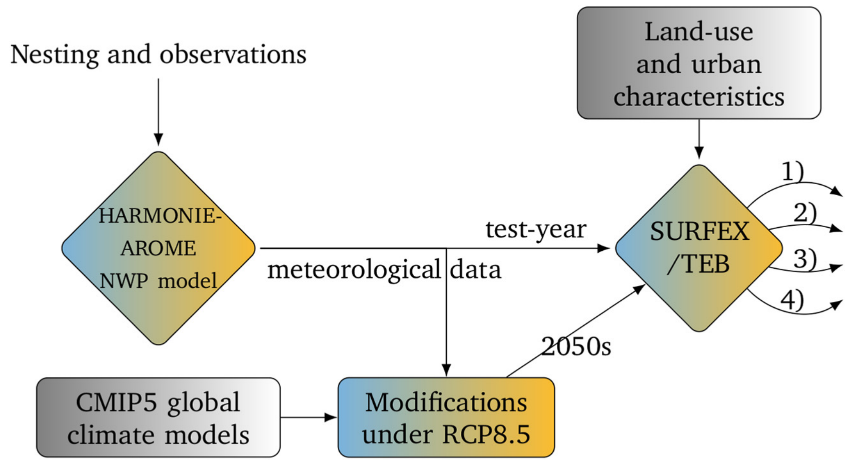

Fig. 1. The model chain used in this study. Hind casts with the limited area numerical weather prediction (NWP) model HARMONIE-AROME were conducted for the test-year months (see Table 2), to create a grid of meteorological data. This meteorological data, called forcing data, was used as input for the surface interaction model SURFEX to simulate recent past urban climate conditions at the surface level on a high-resolution grid. An analogous simulation of the 2050s urban climate was generated by modifying the forcing data using the changes predicted by the Representative Concentration Pathway RCP8.5. In addition, the SURFEX land-use data was modified to simulate the conditions in an area with a green intervention. This approach provided us with four different scenarios: 1) current climate without the intervention, 2) current climate with the intervention, 3) 2050s climate without the intervention and 4) 2050s climate with the intervention. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

taken into account in the simulations. The radiative and thermal properties of the building materials, as well as anthropogenic sources of heat and moisture from traffic and industry and civil buildings were likewise considered.

The intervention of increasing the share of green spaces consisted of replacing all the relatively dense commercial and industrial areas (shown in red colour in Fig. 2) with a suburban type, featuring lower and less dense buildings and a larger fraction of vegetated spaces (Table 1). The changes in urban characteristics are not extreme and take place only over limited areas. Therefore, the effects are expected to be remarkable mainly in the street canyons immediately affected. In particular, we do not expect that such changes would have a significant impact on the whole urban boundary layer. Therefore the same atmospheric forcing (Section 2.2) can be applied to SURFEX before and after the intervention.

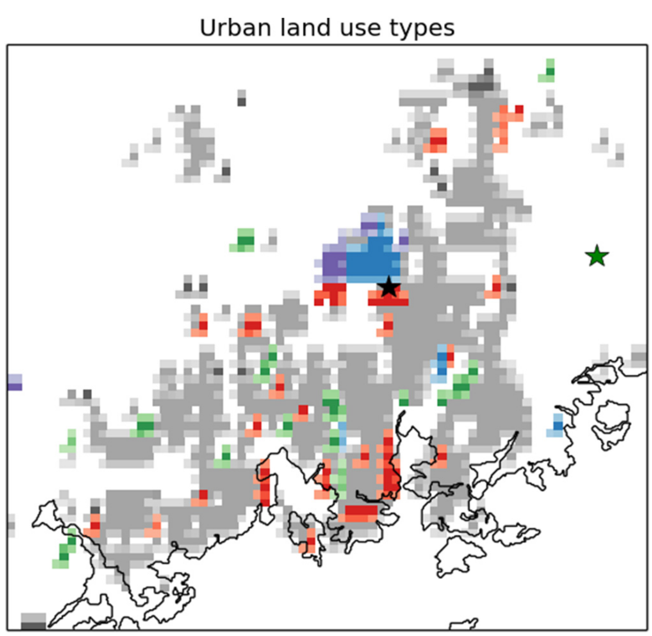

Fig. 2. Urban land use types over the domain considered in the surface interaction model SURFEX. Suburban types are shown in grey, commercial and industrial areas in red, parks and sports facilities in green, and airports and ports in blue colour. Non-urbantypes (sea, lakes and natural or agricultural surfaces) are shown in white. The commercial area of Vantaa Tikkurila and the forest of the Sipoonkorpi National Park are denoted by black and green stars, respectively.

2.2. Methodological approach for the current climate

The high-resolution (0.5 km × 0.5 km) simulations with SURFEX for the current climate were made here in a standalone mode for an artificially constructed test reference year (TRY2012) representing the baseline. The year has been constructed out of 12 historical months that originated from the period 1980–2009 (Kalamees et al., 2012). Following the EN ISO 15927-4 standard, the months were chosen in such a way that the monthly cumulative frequency distributions of daily mean air temperature, relative humidity, solar radiation and wind speed were as close as possible to their respective climatological, i.e., 30-year average, cumulative frequency distributions. As a modification to the standard, in the selection procedure the four meteorological variables were weighted unequally, in order to take into account their importance for building energy demand in Finland. The months selected are listed in Table 2.

It is worth noting that due to the selection method, the test reference year is not intended to studies about extreme weather conditions. Because the largest weight was given to temperature, the variable with the most pronounced changes in the future, we can except that also the adjusted meteorological data for the 2050s is representative of typical climate in Vantaa, assuming RCP8.5 to be materialized.

Due to the standalone mode of SURFEX, hourly time series of meteorological variables were needed as so-called forcing data. The required variables included air temperature, relative humidity, wind speed, rain, snowfall, as well as downwelling solar and thermal radiation. The forcing data at a spatial resolution of 2.5 km were generated for the test-year by the HARMONIE-AROME configuration of the ALADIN-HIRLAM numerical weather prediction system (Bengtsson et al., 2017). Short-

Table 1
Urban characteristics at Vantaa Tikkurila before and after the intervention of reducing the density and height of buildings and adding more widespread green space.

	Building fraction	Building height (m)	Vegetated fraction	Wall surface ratio
Baseline	0.45	20	0.1	0.45
Intervention	0.28	10	0.44	0.28

Table 2
The months of the climatological test reference year for Vantaa (Jylhä et al., 2011).

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1990	1998	1994	2009	2006	2005	2008	2003	1997	1981	1989	1998

range hind-casts were produced four times for each day of the respective months of the test-year, and the hourly meteorological time series were extracted for the SURFEX domain.

2.3. Regional-scale climate projections

Climate change projections were derived from output of global climate models (GCMs) that participated in the latest phase of the Coupled Model Intercomparison Project, CMIP5 (Taylor et al., 2012). The approach of using simulation data from up to 28 different models enabled us to provide robust estimates for the inter-model spread of future climate changes in Vantaa.

2.3.1. Representative Concentration Pathways

In order to simulate future climate change, climate model experiments need assumptions about the future evolution of the atmospheric composition, land use changes and other driving forces of the climate system. The CMIP5 global climate models were run under the Representative Concentration Pathway (RCP) scenario RCP8.5 for global greenhouse gases (GHGs) and aerosols (Taylor et al., 2012; van Vuuren et al., 2011). The RCP4.5 scenario will be shown for comparison, as it represents a less severe climate change. Under RCP4.5, the global mean temperature is projected to increase by 1.4 (0.9–2.0) °C between the periods 1986–2005 and 2046–2065, while under RCP8.5 the projected global warming would be 2.0 (1.4–2.6) °C (IPCC, 2013).

2.3.2. Global climate model simulations

Previous studies (e.g. Luomaranta et al., 2014) have indicated that the 28 GCMs utilized in the present work simulate the northern European recent past climate reasonably well. The names and origins of the GCMs are provided in Table S1 in Section S1 of the supplementary material. The number of models used to construct the climate change projections for the city of Vantaa was 28 for daily mean temperature, precipitation and solar radiation, 25 for daily minimum and maximum temperature and the diurnal temperature range, 23 for relative humidity, 24 for wind speed, 17 for wind directions, and 22 for the monthly standard deviation of the temporal variability of daily mean temperature (Table S1). Model simulations were forced by the observational "historical" GHG concentrations up to the year 2005, after which the concentrations were adopted from the selected RCP scenarios. For relative humidity, supersaturations occurring in the model output data have been truncated (Ruosteenoja et al., 2017).

2.3.3. Construction of the climate change projections

Since the computational grid over the globe varies among the 28 GCMs, model data were first interpolated onto a common $0.5 \times 0.5°$ latitude-longitude grid over Europe (for the wind direction, the resolution was 2.5°). Future trends (expressed as changes per decade) in the climate variables by the 2050s were calculated from differences between the 30-year means of the baseline-period 1981–2010 and the future period 2040–2069. Nonetheless, for the wind directions and the monthly standard deviation of the temporal variability of daily mean temperature, the baseline period was 1971–2000.

As a next step, multi-model means and inter-model standard deviations for the simulated changes were computed. Following Ruosteenoja et al. (2016), the models were weighted equally, with the exception that no individual research center was given more than two votes. The multi-model means can be regarded as "best estimates" for the future climate changes. For a fixed RCP scenario, the spread among the model projections ensues from modelling uncertainty and internal natural variability. Using the standard deviations and the normality approximation, 90% uncertainty intervals for the change were calculated.

2.4. Methodological approach for the future climate

Hourly meteorological data, required as input for SURFEX to simulate urban climate conditions in the 2050s, were generated by modifying the baseline forcing data (Section 2.2) using the climate change projections under the RCP8.5 scenario (Section 2.3). Our approaches fell into the category of morphing, time series adjustment or delta change methods (Belcher et al., 2005; Räisänen and Räty, 2013). The main objectives of the procedures were 1) to minimize the influence of climate model biases; 2) to realistically describe the temporal fluctuations of weather from day to day and hour to hour, including interdependencies among the different climate variables; and 3) to ensure that the statistical properties of the scenario forcing data are consistent with the climate model projections for changes in mean values and (for temperature) variability. The methods for developing the synthetic hourly temperature, precipitation, wind speed and direction, relative humidity and shortwave radiation data are described in detail in Jylhä et al. (2015a), Jylhä et al. (2015b) and Lehtonen et al. (2014). The monthly mean changes in those climatic variables that are needed in the time series adjustment are discussed in Section 3.2 of this article. The temporal evolution of the global GHG emissions and concentrations was assumed to follow RCP8.5.

The hourly totals for snowfall and rainfall provided by HARMONIE-AROME were combined into total precipitation before applying the delta change method. The modified total precipitation was again partitioned into snow and rain using a linear function of the projected future temperature: $P_s = kT + b$, $T \in [-0.5\ °C, 2.0\ °C]$, where P_s is the proportion of snow in the total precipitation, T is the projected future hourly temperature, and k and b are fit parameters calculated from the baseline temperature, rainfall and snowfall data simulated by HARMONIE-AROME. Below −0.5 °C P_s is 1.0 and above 2.0 °C it is 0.

For downwelling longwave radiation, an iterative method was developed to calculate the changes. In this calculation, the relation between the original longwave radiation and air specific humidity was used in conjunction with the projected changes in humidity data. A description of the method can be found in in Section S2 of the supplementary material.

3. Results

3.1. Verification of the HARMONIE-AROME-SURFEX system

HARMONIE-AROME is applied for operational weather forecasting in many European countries including Finland. Its performance is therefore closely monitored and known to meet the demands of a weather service. The same holds true for SURFEX, which is applied in HARMONIE-AROME. Moreover, SURFEX has been found to perform well in an assessment of several surface interaction models operated in standalone mode in the region of our study, while using observed weather parameters as forcing (Karsisto et al., 2016). In this section we compare our model results to observed temperature, relative humidity, wind speed and precipitation amount from Helsinki-Vantaa airport meteorological station (WMO station number 02974). This station is situated over open and even terrain, and has not experienced major changes in its environment during the last decades.

Statistics for the entire representative year mostly indicate a fairly good correspondence between our simulations and the observations

(Table 3). The mean bias and RMSE are mainly small. Correlation coefficients are very high for temperature and somewhat lower for the other parameters -probably because of the relatively pronounced seasonal and diurnal cycles in the temperature. Of the examined parameters, the precipitation amount shows the weakest correlation with observations.

The mean diurnal cycles of temperature are shown in Fig. S2 for all four seasons, each consisting of three months, winter containing December, January, and February, for instance. As the measurements originate from different years and even different decades (Table 2), there are some differences in the measurement intervals. Therefore, the summertime daily cycle (Fig. S2, upper right panel) was obtained from hourly observations while for the other seasons observations were collected in 3 h intervals.

The diurnal temperature cycles are modelled best in spring and autumn. In summer, the simulated daytime temperatures are too high, while in winter night time temperatures tend to be low. Daily mean biases remain below one degree in magnitude in all seasons. The relative humidity (Fig. S3) is likewise best modelled in spring and autumn. Consistently with the overestimated day-time temperature in summer, day-time relative humidity is underestimated in the same season. In winter, the modelled relative humidity is clearly higher than its observed counterpart. The difference could actually be caused by the different definitions of relative humidity in the model and in the observations. For temperatures below the freezing point, SURFEX calculates the relative humidity with respect to ice, while the observations always report the value with respect to water. The latter definition leads to lower values than the former.

The cycles of wind speed (Fig. S4) are modelled well in autumn and winter, but wind speed is consistently underestimated in spring and summer, especially during day time. The pattern is consistent with the overly high values of surface roughness in the model, which could be a result of erroneously high seasonally-varying leaf area index in the model.

Fig. S5 presents the comparison between observed and simulated precipitation amounts. Precipitation totals are well simulated during autumn, winter and spring, when most of the precipitation is related to the passage of frontal weather systems. In summer, when smaller-scale convective systems predominate, larger discrepancies occur, and HARMONIE-AROME tends to underestimate precipitation. Our six-hour long hind casts are probably too short range to allow realistic precipitation systems to form in the model. Underestimated precipitation leading to a loss of soil moisture could be contributing to the warm and dry day-time biases in summer (Figs. S2, S3).

Despite the discrepancies noted above, we believe that our simulations give a reasonably faithful reproduction of the reference year climate. The encountered biases are not likely to significantly affect the conclusions that are based on the differences between our four scenarios.

3.2. Climate change projections

In this section, we first consider multi-model mean climate change projections for Vantaa, based on 28 CMIP5 GCMs, under the RCP4.5 and RCP8.5 scenarios. The spread among the projections, describing the joint uncertainty in the climate change estimates due to modelling uncertainty and internal natural variability, is likewise discussed. Next, we examine how the time series of meteorological parameters used as forcing for SURFEX were modified in order to be consistent with the projected climate change.

3.2.1. Analysis of climate model simulations

Under the RCP8.5 scenario, the projected seasonal mean warming ranges from 0.69 (0.40–0.97) °C per decade in winter to 0.46 (0.21–0.70) °C per decade in summer (Fig. S6a). Expectedly, the increase in daily mean temperatures is invariably lower under RCP4.5 than under RCP8.5. This is generally also true for changes in precipitation, except for summer (Fig. S6b). In summer, the signal of change is weak compared to inter-model differences and noise due to internal variability: the multi-model seasonal mean (the uncertainty interval) is 0.1 (−3.0...3.3) % per decade under RCP8.5. In winter, the seasonal mean rate of change is 2.5 (0.4–4.6) % per decade. The diurnal temperature range is projected to decrease in winter (Fig. S6c), the rate of change under RCP8.5 being −0.16 (−0.30–−0.02) °C decade, while in the other seasons the range alters little.

The projected changes in incident solar radiation (Fig. S6d) resemble those for the diurnal temperature range. Both quantities are tightly linked with clouds. Increasing cloudiness reduces incident solar radiation as well as nocturnal infrared cooling, thereby cutting down the differences between the day-and night-time temperatures. The opposite is true for decreasing cloudiness. One can thus deduce that future winters in Vantaa would become even cloudier (and wetter; see Fig. S6b) but early autumns slightly sunnier than in the recent past.

The day-to-day temperature fluctuations are projected to attenuate in the future not only in winter but also in spring and autumn (Fig. S6e). Only in June and July do the multi-model estimates show small increases both under the RCP4.5 and RCP8.5 scenarios. The uncertainty in changes in monthly mean wind speeds is so large that multi-model mean projections tend to diverge in sign between RCP4.5 and RCP8.5 (Fig. S6f). In all seasons, the share of westerly winds is projected to increase slightly (Fig. S7). The largest change in the frequency distributions of the simulated wind directions is projected to occur in autumn, when the share of southwesterly winds would increase, in absolute terms, by about 1.5 percentage points within seven decades.

3.2.2. Modifications of meteorological forcing for SURFEX

Fig. S8 shows monthly averages of the meteorological forcing for the baseline and for the altered climate of the mid-century following RCP8.5, both for the location of Helsinki-Vantaa airport (the large blue area near Tikkurila in Fig. 2). Clearly, the temperature is the parameter most seriously affected, displaying a warming of a few degrees throughout the annual cycle. For the test-year, all the winter months from December to March show mean temperatures well below freezing, while for the altered climate, this is true only for February. The more modest, but equally systematic, change in relative humidity indicates that the absolute moisture content of the air must be increasing throughout the year. Consistently with the increasing moisture content, downwelling longwave radiation is likewise predicted to increase throughout the year. Little changes are instead observed in the wind speed. From October to January, the amount of precipitation increases by about 10%, while the summer months are less affected. It is worth keeping in mind, however, that summer precipitation in the baseline

Table 3
The mean differences, root mean square errors (RMSE) and temporal correlation coefficients, with *p*-values, between the modelled test-year data and the observed meteorological variables at the Helsinki-Vantaa airport meteorological station. The values are calculated using the data of the whole test-year.

Simulated variable (unit)	Temperature (°C)	Humidity (%)	Wind speed (m/s)	Precipitation (mm/12 h)
Mean difference from the observation	0.07 ± 0.03	0.15 ± 0.14	−0.53 ± 0.02	−0.24 ± 0.07
RMSE	1.7	9.7	1.3	1.6
Correlation coefficient	0.98	0.88	0.84	0.78
p-value	<0.001	<0.001	<0.001	<0.001

test-year forcing data remains well below the measured amounts (Fig. S5).

3.3. Joint impacts of climate change and green infrastructure

3.3.1. Modelled impacts of climate change, current green spaces

In the present climate, the existence of built-up areas in the Helsinki-Vantaa region has a pronounced effect on the simulated climate near the ground. Air temperature is generally higher, relative humidity lower and mean wind speed weaker in the built-up areas than in the surrounding agricultural and forested areas. For air temperature and humidity, the urban influence is strongest during the summer month (July, left panel in Fig. 3); in January (left panel in Fig. 4), the influence is weaker and the distance from the Gulf of Finland tends to dominate the spatial distribution. The urban weakening of the wind speed, by contrast, is most pronounced during winter when winds are strongest on average.

The same patterns as found for the current climate (left panels in Figs. 3–4) are apparent in the projected future climate as well; in other words, when SURFEX is subjected to the altered forcing representing the mid-century. However, the presence of built-up areas tends to reduce the associated (absolute) changes in temperature and humidity in July and in wind speed both in January and July (right panels of Figs. 3–4). For the averages over the 500 m × 500 m grid squares considered, the effects are quite small, amounting to one or two tenths of a degree for temperature, 1 or 2 % for relative humidity, and to about one cm per second for wind speed.

3.3.2. Impacts of the intervention in the present climate

The impact of the intervention to alter the key urban characteristics (Table 1) is explored in a 500 m by 500 m grid cell representing the Tikkurila area in central Vantaa, indicated by a black star in Figs. 2, 3 and 4. Consequences of the intervention in the present climate are

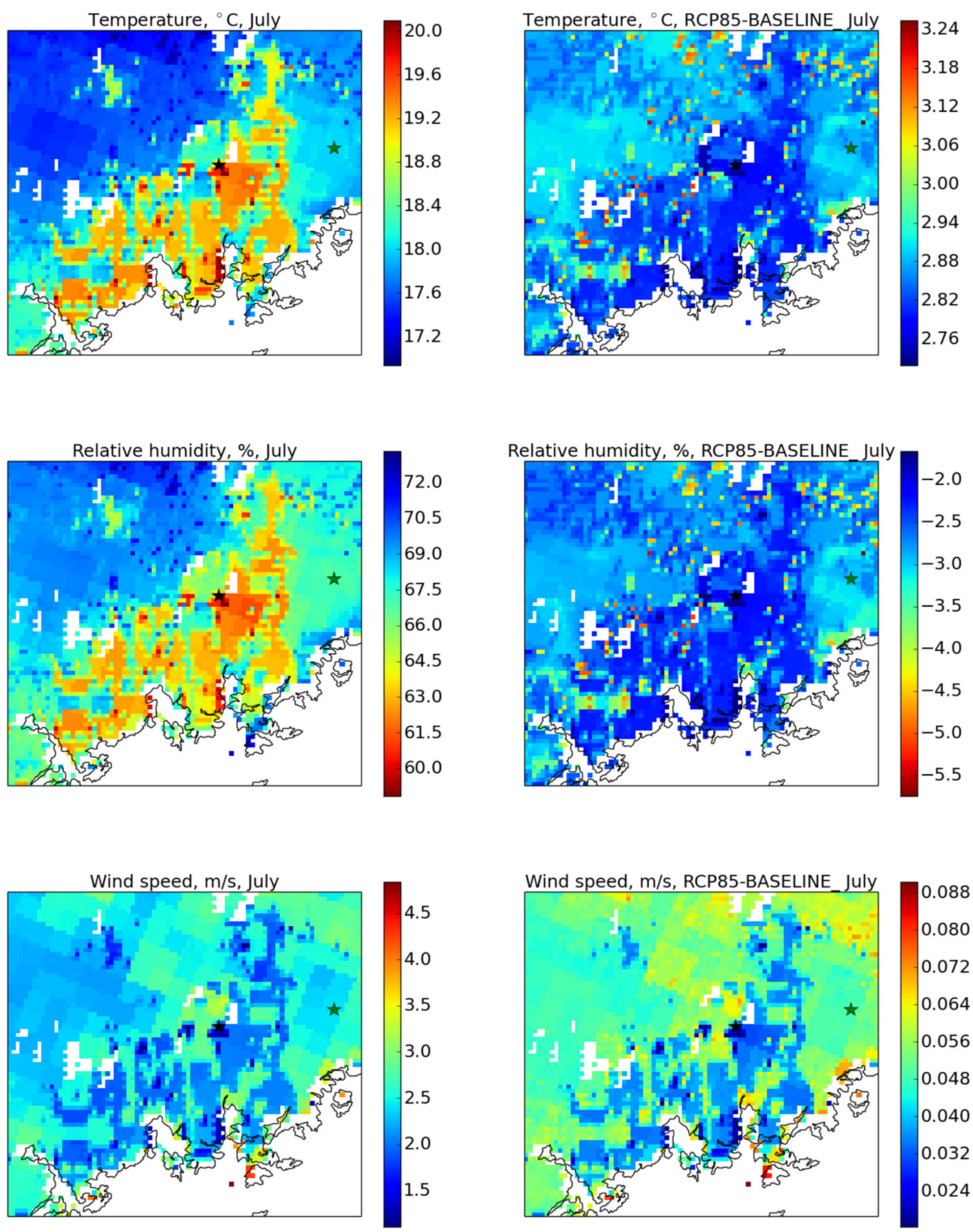

Fig. 3. Monthly mean air temperature (top), relative humidity (middle) and wind speed (bottom) as simulated by the surface interaction model SURFEX in July. Conditions of the test-year, representing current climate, are shown on the left. The high-resolution changes induced by the altered forcing, i.e., regional-scale climate change, are shown on the right. The commercial area of Vantaa Tikkurila and the forest of the Sipoonkorpi National Park are shown by black and green stars, respectively.

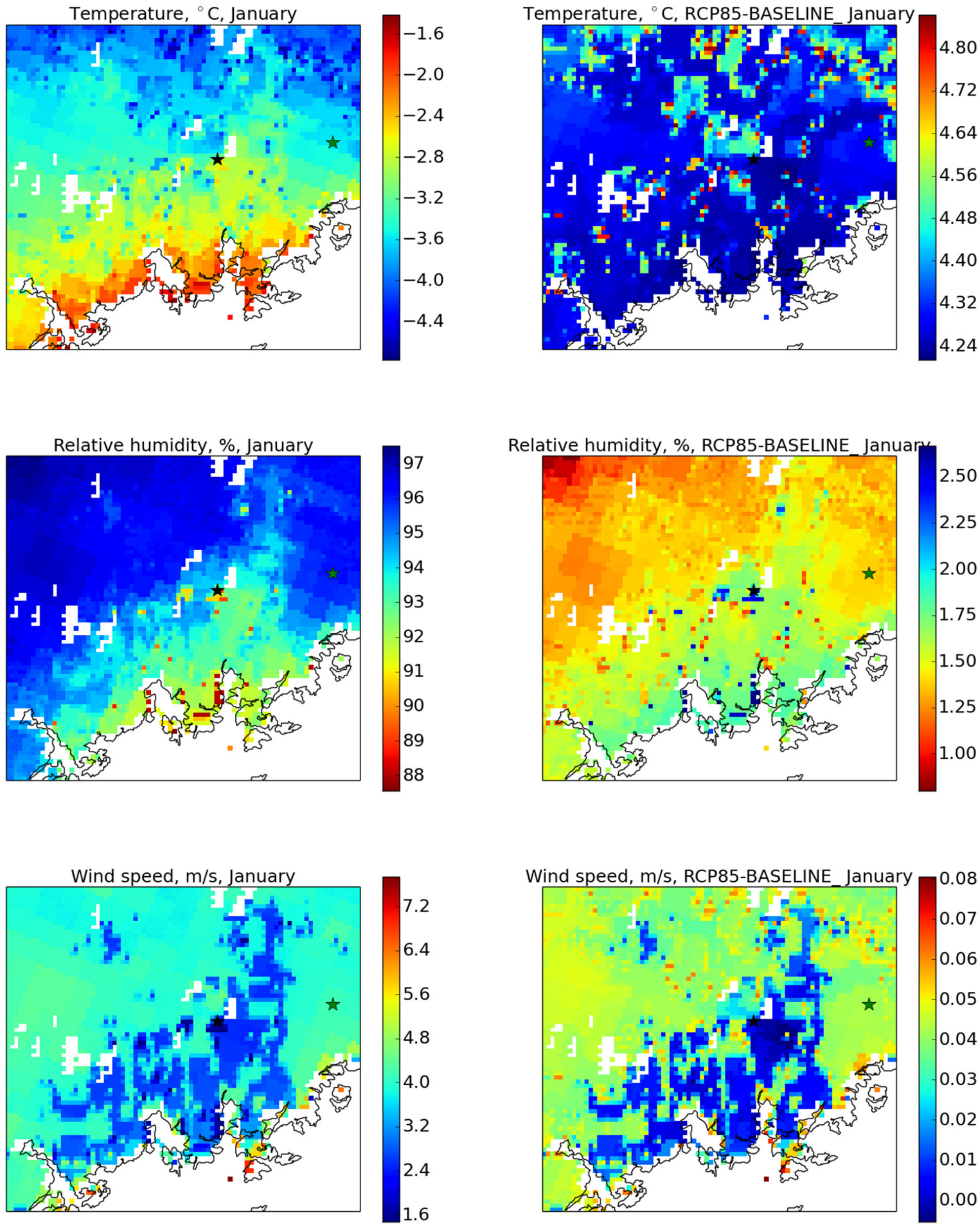

Fig. 4. Monthly mean air temperature (top), relative humidity (middle) and wind speed (bottom) as simulated by the surface interaction model SURFEX in January. Left panels depict the conditions for the test-year, right panels the projected change. For further information, see the caption of Fig. 3.

examined for July (Fig. 5, left column) and January (Fig. 5, right column). For temperature and humidity, the effect of replacing the dense urban layout by a suburban type structure is quite modest but very systematic. On average, the air temperature drops by less than half a degree in January and by more than half a degree in July. In both summer and winter, the change is nearly independent of the baseline temperature. On average, relative humidity increases by about 3 percentage points in summer and winter, but in winter the response is more scattered. The main effect can be seen in the wind speed, which is almost doubled when the sheltering effect of the buildings is reduced.

The fairly minor effect on temperature and humidity is an expected result, as the imposed changes to the urban morphology are rather modest and confined to very small areas. In Vantaa, the difference between "urban" and "suburban" areas is not very dramatic. Moreover, in our study the meteorological forcing represents a grid square of 6.25 km^2 and is not influenced by the intervention at all. The strongest effects would probably be very local and related to individual structures such as buildings or stands of trees, and thus remain unresolved in our experiment.

3.3.3. Impacts of the intervention under changing climate

Simulated meteorological conditions at Vantaa Tikkurila, in the present climate and in the mid-century, both with and without the intervention, are shown in the form of mean diurnal cycles in Fig. 6. For temperature, the intervention causes a cooling of at most about one degree in the afternoon in July, whereas the impact of changing forcing (climate warming) amounts to several degrees in both months. In July, the intervention causes an increase of relative humidity throughout the day, amounting to about 3–5% in the afternoon, while climate change is associated with a drying of a similar magnitude. Conversely, in January, the intervention and climate change both result in a moistening of a few percentage points. Looking at wind speed, the intervention leads to an increase of about 0.5–2.5 m/s, while the impact of climate change is negligible. Thus, changes in the atmospheric forcing

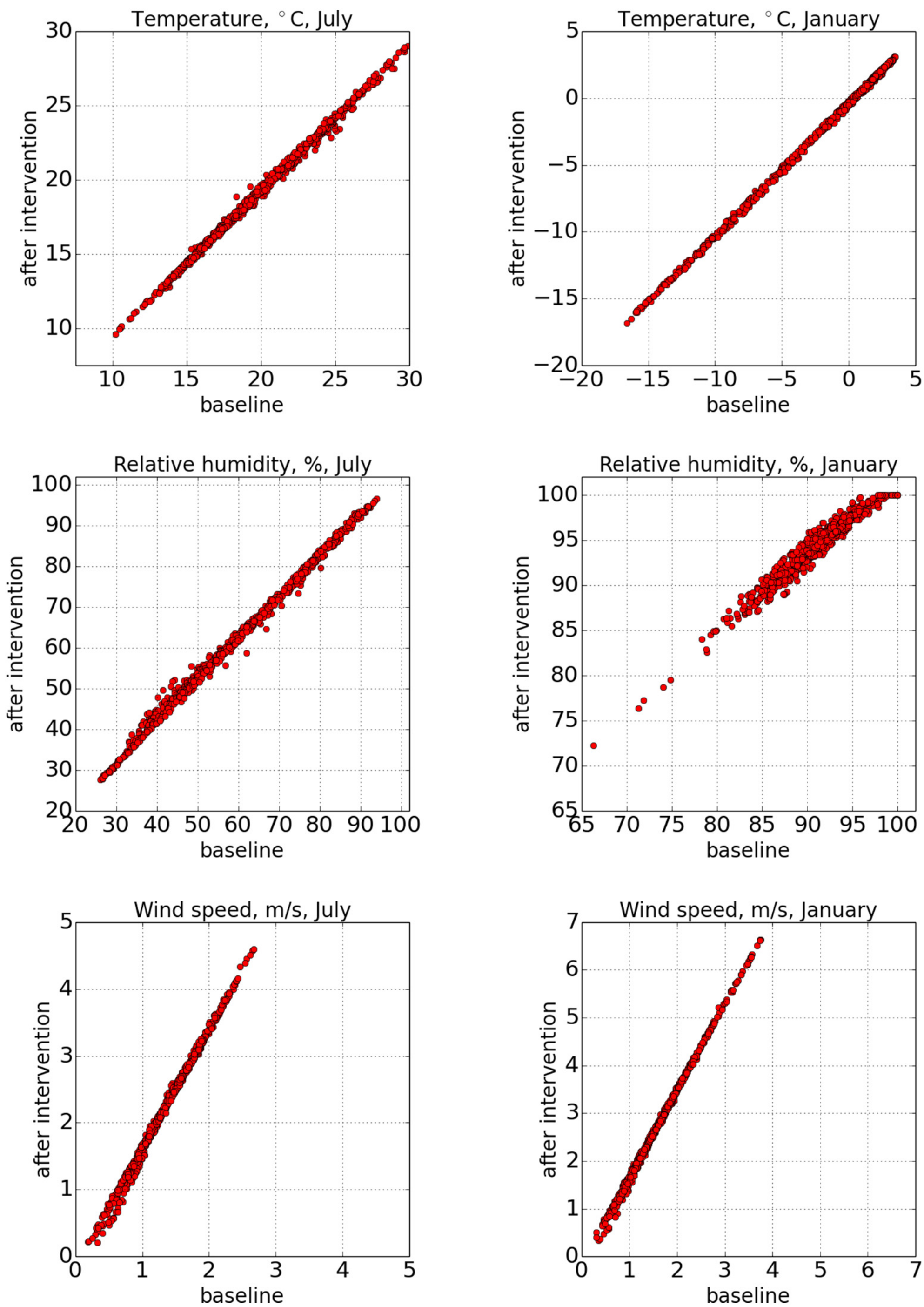

Fig. 5. Scatter plots of air temperature (top panels), relative humidity (middle panels) and wind speed (bottom panels), showing the response to a modification of the urban layout in the surface interaction model SURFEX for the Tikkurila area in Vantaa in July(left column) and January (right column).

(due to larger-scale changes in climate) tend to dominate for temperature, while changes in urban morphology dominate for wind speed. For the relative humidity, changing forcing and changing morphology are of comparable magnitude but of opposite sign in summer.

In Fig. 7, simulated meteorological conditions at Vantaa Tikkurila, in the present climate and in the mid-century, with and without the intervention, are compared with conditions in the forested area of Sipoonkorpi National Park, both at a comparable distance from the coast. Sipoonkorpi National Park is characterized by a mixed forest typical of southern Finland. Looking at the mean diurnal cycles, it can be seen that the intervention acts to reduce the urban heat-island effect (as quantified by the difference between town and countryside) by some 0.5–1° in both January and July, while climate change causes a reduction of about 0.1 degrees (afternoon in July) or less. Relative humidity is lower in Tikkurila than in Sipoonkorpi in July and January, and the intervention acts to reduce the difference in both months by some 3–5 percentage points, while climate change acts to reduce the difference by about 2 points in the afternoon in July, at most. For wind speed, the difference between the two locations is reduced by the intervention by >1 m/s in January and slightly less in July. Again, the effect of changed forcing is negligible. Thus for July and January, we can say that the urban morphology is the dominating factor controlling the difference between the town and the forest wind climate, changing climate being of secondary importance.

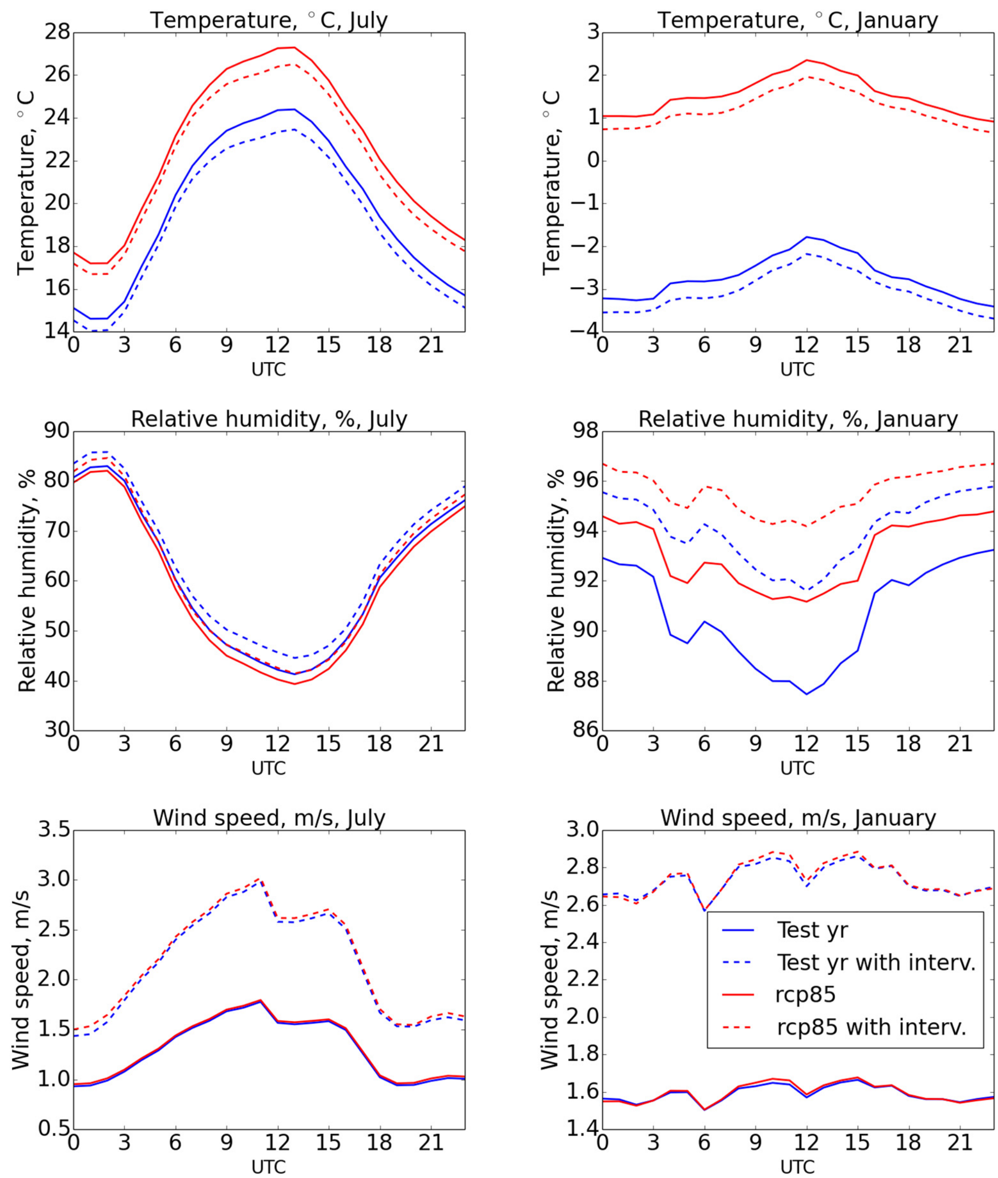

Fig. 6. Monthly mean diurnal cycles of air temperature (top panels), relative humidity (middle panels) and wind speed (bottom panels), showing the response to changing climate and urban layout in SURFEX for Tikkurila in Vantaa in the months of July (left column) and January (right column). Local midday occurs at about 10 UTC. Note the different scales on the y-axes.

Seasonally-averaged results for both climate regimes are given in Tables S2 (temperature), S3 (humidity) and S4 (wind speed). The effect of the intervention and the difference between country-side (Sipoonkorpi) and central Vantaa (Tikkurila) is provided, and they indicate the influence of the city on the local climate. The intervention brings the climate of the city closer to the climate of the country-side in all seasons.

4. Summary and discussion

In this work, the air-surface interaction module SURFEX, with atmospheric forcing obtained from the numerical weather prediction system HARMONIE-AROME, was used to study the climatic influence of the urban and built-up environment within the Helsinki-Vantaa region on the coast of the Gulf of Finland. To assess the impact of climate change, simulations were performed both for an artificially-constructed "test-year" representing the recent past climate of the region and in a future climate corresponding the mid-century under the RCP8.5. The HARMONIE-AROME-SURFEX system was validated by comparing the simulation results with the observations of air temperature, relative humidity, wind speed and precipitation at the Helsinki-Vantaa airport. The inter-comparison shows the annual and diurnal cycles of temperature, humidity and wind speed to be moderately well reproduced by the model system. Precipitation amount, however, is substantially underestimated by HARMONIEAROME during summer, when the precipitation is mainly caused by small-scale scale weather systems such as showers and thunderstorms.

After validation, SURFEX was applied to explore the consequences of altering the urban layout, by replacing relatively densely built commercial and industrial areas with a suburban-type land use featuring lower and less dense buildings and more widespread vegetated areas. For the city of Vantaa, this intervention did not involve any dramatic changes in the urban characteristics, and, not unexpectedly, the effect that was seen in the simulations was mainly rather modest, with the exception of wind speeds that increased substantially as a result of the intervention.

In the present investigation, a built-up area is treated as a homogeneous, isotropic array of street canyons characterized by representative average values of morphological and material parameters describing a grid square of 0.25 km^2. The meteorological forcing, in turn, represents a grid square of 6.25 km^2. Thus, even potentially significant truly local

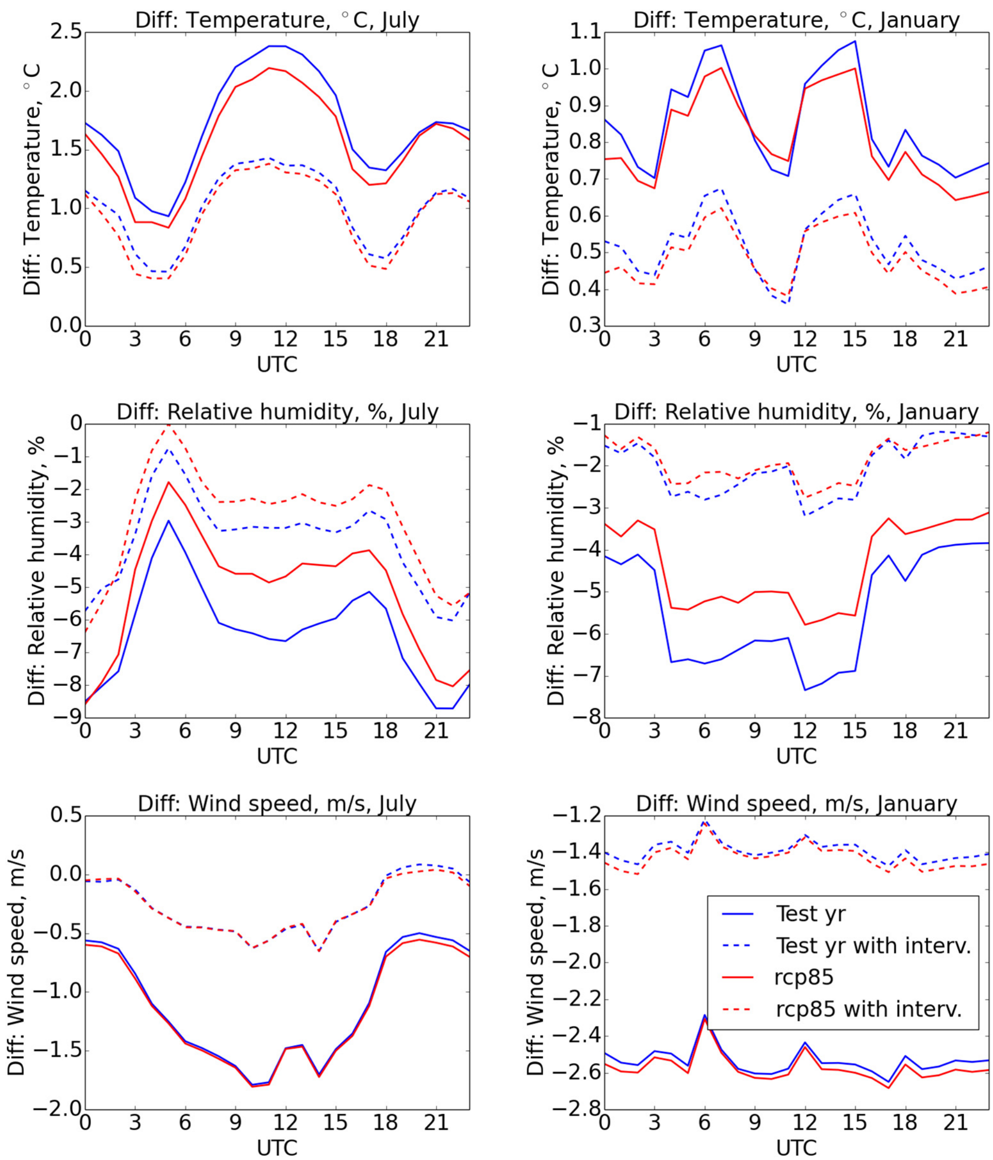

Fig. 7. Monthly mean diurnal cycles of the difference between Vantaa Tikkurila and the Sipoonkorpi National Park for air temperature (top panels), relative humidity (middle panels) and wind speed (bottom panels), showing the response to changing climate and urban layout in the surface interaction model SURFEX for Tikkurila in Vantaa in the months of July (left hand column) and January (right hand column). Local midday occurs at about 10 UTC. Note the different scales on the y-axes.

effects of individual structures such as buildings or stands of trees are not captured. To investigate such effects, the application of a computational fluid dynamics model resolving the flow field around such structures would be needed.

Comparing results for the test-year and the mid-century, it was found that climate warming at the street level was only slightly reduced by the simulated changes in urban morphology. This is in line with the findings of Dong et al. (2019); they found that in China temperature is more sensitive to the projected changes in climate than those in land use. For relative humidity and wind speed, by contrast, changes in morphology had an important or even dominating effect, compared with the changing meteorological forcing due to the global warming. Thus, all the variable changes caused by the intervention are in agreement with previous studies, such as Chen et al. (2018) who studied an opposite city development with increase in urban surfaces.

Since Vantaa is a relatively sparsely-built medium-sized city, the influence of replacing urban environment by suburban-type land use proved to be fairly modest. The impact of the intervention would evidently be far more pronounced in a larger and more densely built city than in the present example. Such a large impact would, however, be felt in the whole urban boundary layer, and simulating it would therefore require modelling the dynamically coupled atmosphere-surface system. The strength of our method resides in its affordability, making it possible to explore several different scenarios for land use and greenhouse gas emissions without recourse to computationally demanding high-resolution climate modelling. This study thus acts as a base for more elaborate model simulations.

CRediT authorship contribution statement

Olli Saranko: Writing - original draft, Validation, Software, Visualization, Formal analysis. **Carl Fortelius:** Supervision, Software, Writing - review & editing. **Kirsti Jylhä:** Resources, Writing - original draft, Writing - review & editing. **Kimmo Ruosteenoja:** Resources, Writing - review & editing. **Erika Brattich:** Validation, Writing - review & editing, Resources. **Silvana Di Sabatino:** Conceptualization, Writing - review & editing. **Väinö Nurmi:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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HARMONIE-AROME and SURFEX simulations have been completed in the ECMWF computing facilities.

The CMIP5 GCM data were downloaded from the Earth System Grid Federation (ESGF) data archive (http://esgf-node.llnl.gov/search/cmip5).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.138471.

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