



Interactions of urban heat islands and heat waves in Swedish cities under present and future climates

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ABSTRACT

The heightened awareness of heat wave impacts in high-latitude cities, particularly after the record-hot summer of 2018, highlights the need for improved understanding of heat waves and Urban Heat Island (UHI) effects. This study focuses on the interaction and future change of heat waves and UHI across southern Sweden under three specific warming levels: 0.9 °C (historical), 2 °C, and 3 °C. We utilize the HCLIM43-AROME convection-permitting regional climate model at 12 km and 3 km resolutions, and the SURFEX land surface model at 300 m resolution, employing a pseudo-global warming approach over target summers (2017, 2018 and 2022) representing different climates.

Our results indicate that the UHI effects are well captured by model simulations. The nocturnal UHI weakens under climate change (assuming no changes in urbanization or greenhouse gas emissions) but intensifies (0.5 °C to 1 °C) during heat waves. During heat waves, higher sea level pressure, radiation and sensible heat flux contribute to enhanced urban warming due to higher thermal inertia. The nocturnal UHI is further accentuated by lower wind speeds and cloud fraction (indicative of weaker advection), lower moisture flux, and decreased soil moisture (associated with reduced evaporation) in urban areas during heat waves. These nuanced findings provide valuable insights for local heat stress adaptation strategies, with future research needed on the impacts of urban expansion.

1. Introduction

The observed trends of heat waves are expected to continue and accelerate across nearly all inhabited regions as anthropogenic climate change intensifies (Domeisen et al., 2023). Future warming, urban expansion and densification could lead to more extreme heat waves with associated risks of morbidity, mortality and economic losses (e.g., Li and Bou-Zeid, 2013; Scott et al., 2018), particularly over urban spaces, which are now home to 4.2 billion people (Hoegh-Guldberg et al., 2018; IPCC, 2021; Dodman et al., 2022). Moreover, cities frequently exhibit higher air temperatures than their surrounding suburban and rural areas, particularly during

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nighttime, a phenomenon widely recognized as the urban heat island (UHI) effect. The IPCC's special report on 'the impacts of global warming of 1.5°C' (Hoegh-Guldberg et al., 2018) states that urban heat islands often amplify the impacts of heatwaves in urban areas. Understanding the processes in heat waves and UHI becomes essential to assess and reduce heat exposure.

The UHI is a complex physical process influenced by a number of factors, including wind speed (Li et al., 2016; Rogers et al., 2019), cloud cover (e.g., Oke, 1982; Morris et al., 2001), land surface properties (e.g., Lauwaet et al., 2016; Keat et al., 2021), land use and land cover (Ngarambe et al., 2020; Kabisch et al., 2023), atmospheric scales (Chen et al., 2023), anthropogenic heat (Ramamurthy and Bou-Zeid, 2017; Zhao et al., 2018), background climate (Zhao et al., 2018; Jiang et al., 2019), city sizes (Ramamurthy and Bou-Zeid, 2017), among others. An important unresolved question pertains to the changes in UHI intensity during heat waves. While some studies suggest an increase in UHI (Li and Bou-Zeid, 2013; Schatz and Kucharik, 2015; Li et al., 2016; Founda and Santamouris, 2017; Ortiz et al., 2018; Jiang et al., 2019; Ngarambe et al., 2020; An et al., 2020), others indicate a decrease (Scott et al., 2018; Kumar and Mishra, 2019; Rogers et al., 2019; Richard et al., 2021) or no change at all during heat waves (Ramamurthy and Bou-Zeid, 2017; Chew et al., 2021). Many of these studies have highlighted the importance of background climate in UHI and heat wave interactions. Park et al. (2023) identified positive interactions between UHIs and heat waves during strong UHI days, but negative interactions during weak UHI days in Seoul, attributing these interactions to varying weather conditions under different synoptic patterns. Zhao et al. (2014, 2018) concluded that the interaction between UHI and heat waves is significantly sensitive to local background climate (e.g., dryness) in their study of US cities. Jiang et al. (2019) found that the amplification of UHI under heat waves varies in Beijing, Shanghai, and Guangzhou due to different local background climates, with solar radiation and wind direction playing significant roles.

Furthermore, future projections of UHI change based on model simulations also vary across studies, predicting either an increase (e.g., Levermore et al., 2018; Tewari et al., 2019; Lo et al., 2020; Doger de Speville et al., 2023), a decrease (Lauwaet et al., 2016; Lind et al., 2022), or no change (Keat et al., 2021) in UHI intensity. In UK cities, the future UHI intensity is unchanged in UK Climate Projections (UKCP) convection-permitting regional climate model (CPRCM) simulations at 2.2 km (Keat et al., 2021), but an increasing trend of summer night-time UHI intensity has been observed in simulations using the UKCP18-regional climate model at 12 km (Lo et al., 2020; Doger de Speville et al., 2023). They attributed this difference to the larger drying of future RCM (at 12 km) soils compared to the CPRCM (at 2.2 km). Tewari et al. (2019) found that a warmer climate in the future tends to amplify the UHI intensity during heat waves in both Phoenix (21 %) and NYC (48 %) using Weather Research and Forecasting (WRF) model, but such intensification is of large uncertainty with large temporal variation in UHI.

Most studies on future change of UHIs and their interactions with heat waves have focused on mid to low latitudes (e.g., western and southern Europe, Asia, and America), with limited studies over high latitude regions, which experience different meteorological conditions and local background climates (Zhao et al., 2014; Kong et al., 2021; Cheval et al., 2024). These differences can lead to varying UHI intensities during heat waves (e.g., Ao et al., 2019; An et al., 2020), resulting in different interactions between UHIs and heat waves. The IPCC released projections of 2–4 °C increased temperatures of the hottest days in Northern Europe under global warming of 1.5 °C compared to the pre-industrial period (Hoegh-Guldberg et al., 2018). Sweden experienced a very long warm summer with an unusually high number of hot days in 2018 (Wilcke et al., 2020). This heat wave had significant consequences, including an increase in mortality rates (Läkartidningen, 2019). These issues have raised the awareness of the potential heat wave impacts in high latitude cities. Heat waves are relatively rare over high latitudes compared to low-mid latitudes, but temperatures that are normal in hotter climates can cause heat stress for people living in cooler climates who are not adapted to higher temperatures. Previous studies have examined UHIs and heat waves in Nordic cities (e.g., Räsänen et al., 2019; Schwaab et al., 2021; Berghald et al., 2024) and the Arctic region (e.g., Varentsov et al., 2018; Miles et al., 2023). However, none of these studies have investigated the interactions between UHI and heat waves or the future changes in UHI. The current study seeks to contribute with insights into this inconclusive aspect of future UHI changes and their interactions with heat waves over high latitude cities.

Recently, CPRCMs incorporating urban parameterizations in the land surface component have proven valuable for simulating urban climates. These models run at spatial resolutions as high as sub-kilometer scale and show great benefits over urban areas characterized by strong spatial heterogeneities (Mussetti et al., 2020; Amorim et al., 2020; Wang et al., 2023). Nevertheless, the computational expense of high resolution CPRCMs limits their practical application. In this study, we propose to downscale specific periods of interest through time-slice simulations (Cholette et al., 2015) instead of simulating over a continuous long time period to encompass all events. This novel approach allows for simulating numerous events with a CPRCM at reduced computing costs compared to traditional continuous simulations.

Specifically, the aims of this study are: (1) to assess the performance of the time-slice simulation approach in modeling heat wave and UHI; (2) to investigate the projected changes in heat waves and UHI under future climate; (3) to explore the interactions between UHI intensity and heat waves and the mechanisms underlying these relationships. In this study, we use the CPRCM HCLIM-AROME (Lindstedt et al., 2015; Belušić et al., 2020) to downscale to 12 km and 3 km resolutions. To further downscale to even higher resolution (hundreds meters scale) for climate change adaptation support, the land surface component SURFEX (Surface Externalisée, Masson et al., 2013) of HCLIM-AROME is used (Wang et al., 2023) in offline configuration. The study focuses on two regions in southern Sweden: Stockholm and Norrköping-Linköping. These regions have a humid continental climate with warm summers and year-round precipitation. We focus on three summers representing different climate conditions over southern Sweden. The pseudo-global warming (PGW) approach is used to project these summers under three Specific Warming Levels (SWL, Bärring and Strandberg, 2018) above pre-industrial periods: 0.9 °C (historical), 2 °C and 3 °C.

2. Method

2.1. Models

The Harmonie-Climate (HCLIM, Lindstedt et al., 2015; Belušić et al., 2020) Regional Climate Model (RCM) contains different atmospheric physical packages and here we specifically use HCLIM version/cycle 43 with the AROME atmospheric physical package. HCLIM43-AROME runs with nonhydrostatic dynamics at 75 s time step with both 12 km and 3 km grid spacing. SURFEX (Masson et al., 2013) Land Surface Model (LSM) contains various physical models that enable the simulation of surface processes in HCLIM. Subgrid surface heterogeneity is represented by four tiles, encompassing continental natural surfaces, sea, inland water and urban areas. Urban surfaces are modeled using the TEB (Town Energy Balance; Masson, 2000) scheme that is based on the Urban Canyon approach (Nunez and Oke, 1977). The TEB scheme offers the flexibility to simulate urban green areas by the GARDEN (Lemonsu et al., 2012) and the GREENROOF modules (De Munck et al., 2013). The representation of trees within urban areas is available since SURFEX v8.0 (Redon et al., 2017; Redon et al., 2020). Natural surfaces are parameterized using the ISBA model (Noilhan and Planton, 1989), while inland water is simulated by the lake model FLake (Mironov et al., 2010). Sea surface temperature is obtained from an external data source. In this study, SURFEX v8.1 is used in both HCLIM43-AROME and offline simulations. The TEB model with a single-layer urban canopy model and the default force-restore building energy model (Masson et al., 2002) is applied.

The HCLIM43-AROME 3 km simulation is nested within HCLIM43-AROME 12 km simulations. An 11-grid-point extension zone, which extends dynamical fields to maintain periodicity across the entire domain, has been removed in both the 12 km and 3 km simulations (Lindstedt et al., 2015). Aside from the difference in resolution, the setups of the two HCLIM simulations are identical. Hourly outputs from HCLIM43-AROME at 3 km are bilinearly interpolated to 300 m and then used to force SURFEX offline simulations (Wang et al., 2023). The offline SURFEX model is the same as that used in HCLIM43-AROME. Atmospheric forcing variables provided

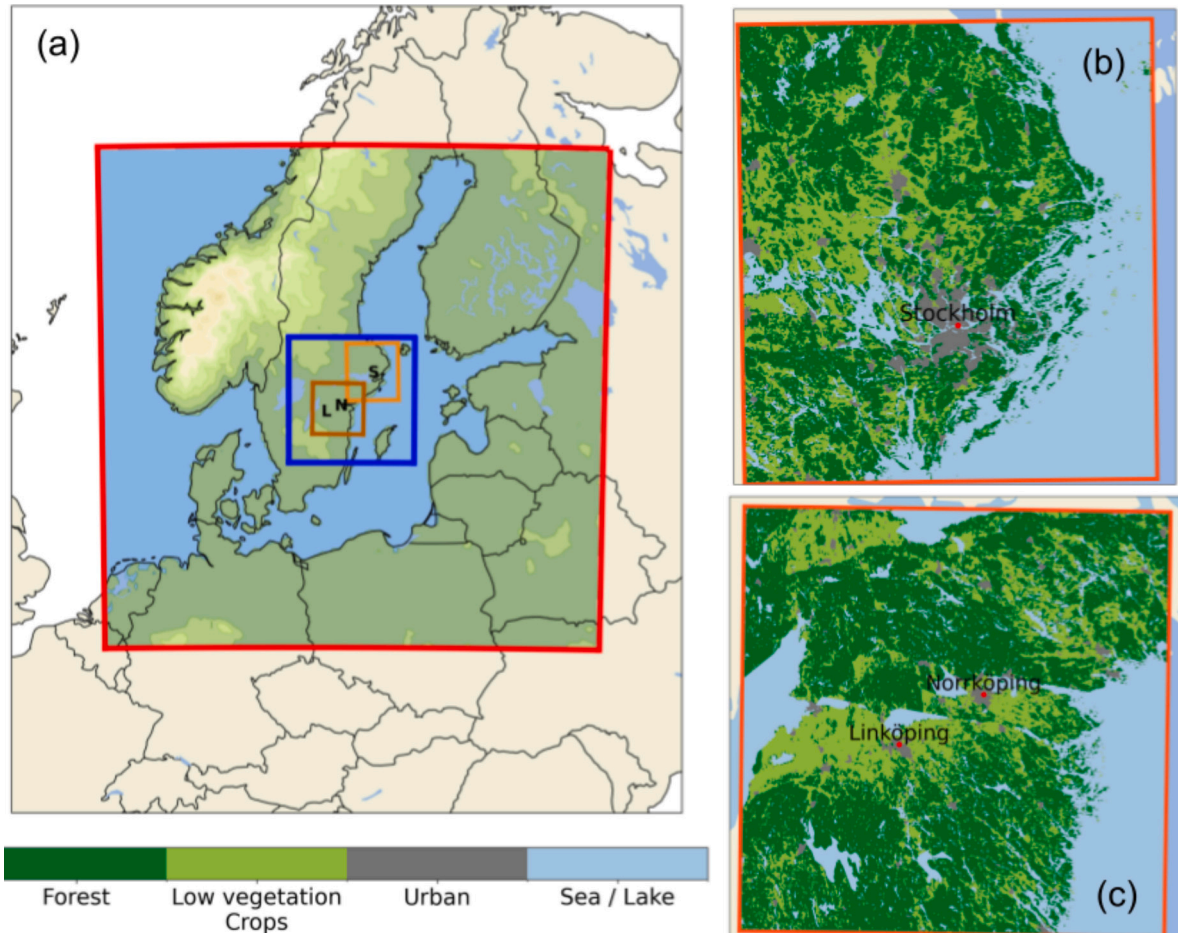


Fig. 1. The simulation domain for HCLIM43-AROME (a, 12 km in red, 3 km in blue), SURFEX offline at 300 m over Stockholm (b) and Norrköping-Linköping (c). Domain sizes for the 12 km, 3 km, Stockholm 300 m, and Norrköping-Linköping 300 m grids are 150×150 , 150×150 , 576×640 , 576×576 (longitude $\times$ latitude), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to the offline SURFEX model include rainfall rate, snowfall rate, surface pressure, surface downward short-wave radiation (both direct and scattered), surface downward long-wave radiation, 2 m air temperature, 2 m specific humidity, and 10 m wind speed and direction above the urban canopy layer.

Compared with the previous version HCLIM38 (Belušić et al., 2020; Lind et al., 2020, 2022), several new features are implemented in HCLIM43. These include the replacement of the land cover data ECOCLIMAP V2.2 by the latest version Second Generation (SG), which is produced at 300-m resolution and includes ten urban cover types corresponding to the ten Local Climate Zones (see Druel et al., 2022 and <https://opensource.umr-cnrm.fr/projects/ecoclimap-sg/wiki>). Additionally, the sand and clay dataset has been updated from FAO to SoilGrids250m version 2.0 (<https://soilgrids.org/>). Another significant addition is the implementation of the Multi-Energy Balance scheme (Boone et al., 2017) within SURFEX, among other improvements.

2.2. Datasets

Four different observational and reanalysis datasets are used in this study. E-OBS is a daily gridded observational dataset over land area of Europe from 1950 to present period (Cornes et al., 2018; Copernicus Climate Change Service, 2024). It is based on station observations directly obtained from the European national meteorological and hydrological services or other relevant data-holding institutions. In this study, we use E-OBS version 27 with $0.1^\circ \times 0.1^\circ$ spatial resolution. The Copernicus European Regional ReAnalysis (CERRA) dataset integrates model data with observations, spanning from September 1984 to June 2021 (Schimanke et al., 2021; Ridal et al., 2024). In this study, we use the high-resolution CERRA reanalysis at a $5.5 \text{ km} \times 5.5 \text{ km}$ horizontal resolution with a temporal resolution of 3 h. Ground-based observations, collected during the summer of 2022 in Norrköping-Linköping, include stations situated in both urban and rural areas at heights of 2–3 m above the surface (see Table A1 for station details). Near-surface air temperatures from E-OBS, CERRA datasets and ground-based observations, along with surface relative humidity from ground-based observations, are used to evaluate the model simulations by HCLIM and SURFEX. ERA5 is the fifth generation ECMWF atmospheric reanalysis of the global climate at $0.25^\circ \times 0.25^\circ$ resolution covering the period from January 1940 to present (Hersbach et al., 2023). The ERA5 data is used to generate the Lateral Boundary Conditions (LBCs) for HCLIM43-AROME at 12 km resolution utilizing the PGW approach (see section 2.4.2).

2.3. Study domain

The two study domains consist of the areas of Stockholm and Norrköping-Linköping (Fig. 1). In the urban area, the population was 1,617,407 in Stockholm, 115,682 in Linköping and 98,088 in Norrköping, as of 2020 (SCB Statistikmyndigheten, 2022). The urban area covered 422.43 km², 37.43 km², and 37.55 km², respectively for these three cities, as of 2020 (SCB. Statistikmyndigheten, 2021).

Fig. 1a shows the model simulation domains for HCLIM43-AROME at 12 km and 3 km. Fig. 1b and c show the further downscaled simulations to 300 m by SURFEX over the Stockholm and Norrköping-Linköping domains, respectively. The computational domain for the SURFEX offline simulation is smaller than the HCLIM43-AROME 3 km simulation to avoid potential spatial spin-up inaccuracies at the lateral boundaries of the HCLIM43-AROME simulation.

2.4. Experiments design

2.4.1. Event selection

We selected 3 summers in southern Sweden to represent different climate conditions. Specifically, we selected the summers of 2017, representing an average summer (SMHI, 2017), 2022, embodying an average heatwave (SMHI, 2022), and 2018, depicting an extreme heatwave event (SMHI, 2018).

The summer of 2017 (EV1) experienced a prevalence of low-pressure systems, mainly from the west, resulting in significantly cooler weather in Northern Europe. Despite the absence of high temperatures during the 2017 summer, the overall values closely aligned with the normal range over the reference period of 1961–1990. In contrast, the summer of 2022 (EV2) experienced above-average temperatures, particularly in the eastern regions of the country, as compared to the normal period of 1991–2020. The summer of 2018 (EV3) was warmer than normal throughout the country. In the northern part, the temperature anomaly ranged from 1 to 3 °C, while in the south, it was 2 to 4 °C higher. Several stations with extensive measurement histories, including Uppsala (recorded since 1722), Stockholm (since 1756), Lund (since 1859), and Gothenburg (since 1860), documented new records for summer mean temperature.

2.4.2. Dynamical downscaling of representative summer climate events

Since the Paris Agreement, the urgency to understand the implications of a 1.5 °C or 2 °C warmer world has grown. This shifts the focus from temperature at a specific time to the climate conditions at a given temperature increase, or SWL, regardless of when this level would be reached (Barring and Strandberg, 2018). By definition, the global mean temperature at a SWL remains consistent across all models and scenarios. For these reasons, we use SWLs rather than Shared Socioeconomic Pathways (SSPs) in this study. We conducted simulations for each event under three globally calculated SWLs: SWL0.9, SWL2 and SWL3, corresponding to temperature increases of 0.9 °C, 2 °C and 3 °C above pre-industrial levels, respectively. The climate conditions of these SWLs are obtained from EC-Earth large ensemble simulations (S-LENS; Wyser et al., 2021). The S-LENS consists of a 50-member ensemble of simulations for each scenario, covering a total of eight SSP scenarios over both historical (1970–2014) and future periods in the 21st century. For this study, the S-LENS simulations under SSP3–7.0 are used to calculate the climate conditions corresponding to the different SWLs. The SWL0.9

corresponds to historical climate, which is calculated as the ensemble mean SWL for 1995–2014 (0.892 °C). Totally, there are 9 simulations of 3-month length performed by each model, corresponding to the combination of the three summers (2017 for EV1, 2022 for EV2, 2018 for EV3) and the three SWLs (SWL0.9, SWL2, SWL3) selected.

Our methodology incorporates the PGW approach as described by Brogli et al. (2023), which imposes the large-scale Global Climate Model (GCM)-based climate change signal on the boundary conditions of a regional climate simulation (Fig. 2). Firstly, the annual forcing corresponding to SWL0.9 is calculated by EC-Earth historical simulations over the period 1995–2014 (referred to as EC-Earth-HIST). Secondly, within each EC-Earth S-LENS ensemble member, we compute a 20-year average that reaches a specific SWL and identify the year within this 20-year period that best approximates the desired SWL. The boundary conditions corresponding to this specific year for each ensemble member are saved from EC-Earth. The climate change signals (Δ) for each EC-Earth S-LENS ensemble member are calculated as the difference between each ensemble member's selected year at the given SWL and the EC-Earth-HIST. Thirdly, we calculate the ensemble mean of Δ across all 50 ensemble members in EC-Earth for SWL2 and SWL3. Specifically, the Δ are computed for air temperature, relative humidity, zonal and meridional wind components, surface air pressure, and surface temperature. Fourthly, we interpolate these Δ based on ERA5 temporal and spatial resolutions and integrate them into the ERA5 dataset. This modified dataset, created by adding the Δ to ERA5, serves as the updated set of LBCs for HCLIM43-AROME at 12 km resolution. The Δ is applied the same way to each summer in ERA5 (2017, 2018, 2022).

The current experimental setup significantly reduced computing time compared to the traditional method of running continuous simulations from 2017 to 2022 to cover all three summers. To initialize the HCLIM43-AROME model, we conducted offline runs of its land component SURFEX spanning over a period of more than 30 years, which were subsequently followed by a few months of HCLIM43-AROME simulations.

2.5. Analysis method

To calculate the UHI intensity, we defined urban and rural areas surrounding each city based on city size and the fraction of SURFEX tiles (Fig. A1), with varying fraction thresholds defined for different models to ensure consistency in grid point usage. Specifically, urban grid points were defined where the urban tile fraction exceeds 20 % (10 % for Norrköping-Linköping domain) for HCLIM43-AROME at 12 km (HCLIM12), 20 % for HCLIM43-AROME at 3 km (HCLIM3) and 99 % for SURFEX offline simulations at 300 m (SURFEX 300 m), respectively. It should be mentioned that urban areas situated far from Stockholm city center (e.g., Uppsala) are not included in the urban areas from the Stockholm domain. Rural grid points were identified where the nature tile fraction exceeds 80 %, 90 % and 99 % for HCLIM12, HCLIM3 and SURFEX 300 m, respectively. The selected tile fraction thresholds for urban are based on a compromise among several criteria: (1) ensuring a sufficient number of grid points for urban areas, (2) maximizing the overlap of urban areas among the HCLIM12, HCLIM3, and SURFEX 300 m models, and (3) achieving a clear distinction between urban and rural areas. It should be noted that the low urban fraction thresholds used to delineate urban areas in HCLIM12 and HCLIM3 are necessary

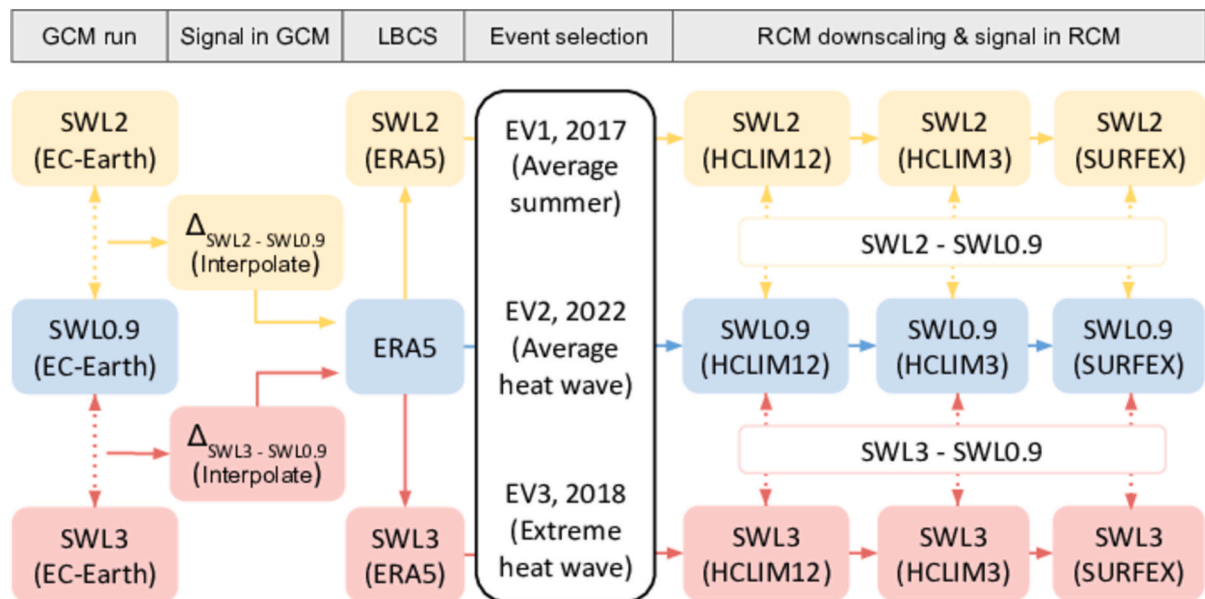


Fig. 2. The schematic of the simulations. The deltas (Δ) calculated from the EC-Earth GCM, represented in yellow for SWL2 and in red for SWL3, are added to ERA5 global reanalysis. The original and modified ERA5 data are used as LBCs for HCLIM43-AROME 12 km for each of the 3 selected climate events (in black box). The 12 km simulation is further downscaled to 3 km resolution by HCLIM43-AROME and subsequently to 300 m resolution by SURFEX LSM under the 3 SWLs for each climate event. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

due to the urban areas' sizes (see section 2.3) relative to the model grid box areas. Despite low thresholds, this approach can still clearly capture the UHI effects. However, increasing the threshold for urban tiles, such as to 30 % for HCLIM12 could result in just two grid points representing urban areas in the Stockholm domain. Nonetheless, we evaluated the results for a 30 % threshold in Stockholm, and using values only over the urban tiles of each model grid over Stockholm and Norrköping-Linköping, confirmed that the conclusions related to UHI obtained from this study remain qualitatively unchanged, even though the absolute value of UHI intensity may vary. To mitigate influences from sea and inland water bodies, selected urban and rural grid points were excluded if their sea or inland water tile fractions exceeded 20 %, 10 %, and 1 % for HCLIM12, HCLIM3 and SURFEX 300 m, respectively. The same methodology was applied to observational/reanalysis data, which were interpolated to the SURFEX offline simulation grid at 300 m resolution.

The UHI intensity ($^{\circ}\text{C}$) was calculated as the difference in 2-m air temperature between urban (T_u) and rural (T_r) areas. To assess future UHI changes, we employed the linear, total least squares regression method as used by Scott et al. (2018) on the future changes of T_u (ΔT_u) and T_r (ΔT_r) under SWL2 and SWL3 relative to their historical values (SWL0.9). We also calculated the Pearson coefficients between UHI intensity and meteorological variables to understand the UHI variation processes. Statistical significance of the Pearson correlation coefficient and slope in the total least squares regression was assessed using Student's *t*-test (at a significance level of 0.05). The time periods of 15:00–18:00 and 00:00–03:00 (local time) were chosen to represent daytime and nighttime, respectively. This selection is based on the extended summer daylight hours at the high latitudes of Stockholm (59°N), Norrköping (58.6°N), and Linköping (58.4°N).

3. Results and discussion

3.1. Evaluation with observations and reanalysis data

3.1.1. 2-m air temperature and 2-m relative humidity

Fig. 3 compares daily T_{2m} between observations/reanalysis (EOBS27 and CERRA) and model simulations, averaged over the Stockholm and Norrköping-Linköping domain. The averaging is performed within the SURFEX domain (Fig. 1b and c), with grid cells covering lakes and sea areas exceeding 20 % (HCLIM12), 10 % (HCLIM3) and 1 % (SURFEX) excluded to mitigate influences from water bodies. The simulations closely follow the T_{2m} variations across all three climate events. Over urban grid points, HCLIM43-AROME at 3 km and SURFEX at 300 m outperformed HCLIM43-AROME at 12 km (Fig. A2).

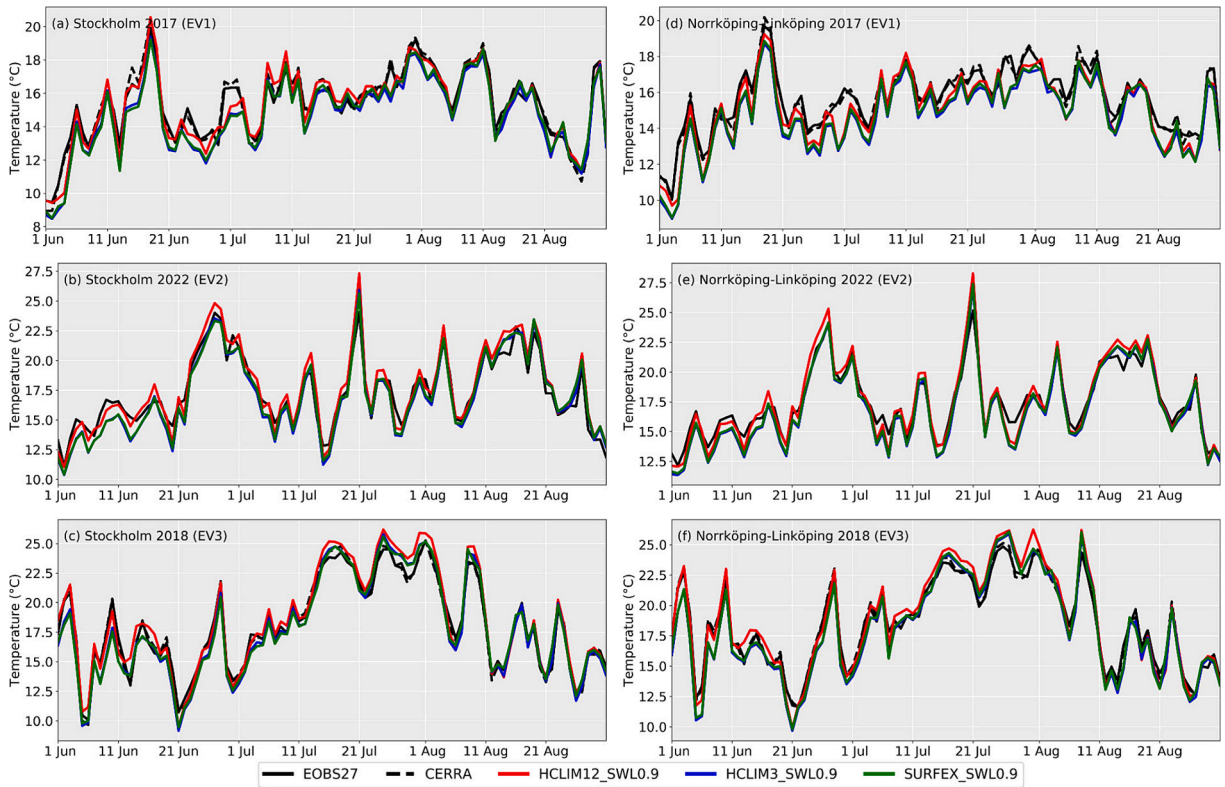


Fig. 3. Comparison of daily T_{2m} ($^{\circ}\text{C}$) between observations/reanalysis and model simulations (HCLIM43-AROME at 12 km and at 3 km, SURFEX at 300 m) over historical period (SWL0.9) averaged over Stockholm (a, b, c) and Norrköping - Linköping (d, e, f) domains for EV1 in 2017 (a, d), EV2 in 2022 (b, e) and EV3 in 2018 (c, f).

Fig. 4 displays the spatial distribution of daily minimum T_{2m} from reanalysis/observations and model simulations averaged over the JJA period, focusing on EV3 in 2018. Generally, clear UHI effects are observed in both model simulations and EOBS27/CERRA datasets, with the UHI intensity higher in model simulations than in EOBS27/CERRA. While domain-averaged values are comparable between model simulations and observational/reanalysis datasets, ranging from 11.55 °C to 13.14 °C for Stockholm and 11.51 °C to 13.22 °C for Norrköping-Linköping, the spatial structure of T_{2m} becomes more distinct with increased model spatial resolution. This detailed spatial distribution information of T_{2m} is crucial for local decision-making processes (also see Fig. A3).

It should be noted that both EOBS27 and CERRA have limitations and uncertainties, and the differences between model simulations and EOBS/CERRA do not necessarily imply poor model performance. In CERRA, the urban model is inactive, with urban areas treated as rock and incorporated into natural land categories (Ridal et al., 2024). Additionally, the EOBS27 (at 0.1° resolution) has limited and uneven distribution of observation stations within the study domain's urban areas (7 stations in Stockholm and 6 in Norrköping-Linköping) used in EOBS27, as indicated by the study area's metadata (https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php). Van der Schrier et al. (2013) also noted that urbanization introduces uncertainty in temperature of EOBS data. To further evaluate model performance, we compared the diurnal cycles of 2-m air temperature (Fig. 5) from model simulations with ground-based observations for June–August 2022 in the Norrköping-Linköping region. The results show that SURFEX 300 m and HCLIM3 simulations outperform HCLIM12, highlighting the importance of high-resolution modeling for accurately representing urban climates. The same conclusion holds when comparing 2-m relative humidity from model simulations with ground-based observations (Fig. A4).

3.1.2. UHI intensity

We calculate the UHI intensity utilizing daily minimum T_{2m} (Fig. A5), and the UHI intensity in model simulations is assessed by comparing them with observations. The choice of daily minimum value is driven by the availability of EOBS27 dataset and the fact that UHI is mainly a nocturnal phenomenon (e.g., Oke et al., 2017; Amorim et al., 2020). Generally, the simulated UHI is higher for all models than observations, over both the Stockholm and Norrköping-Linköping regions (Fig. 6). To further evaluate UHI in the model simulations, we compare them with ground-based observations in the Norrköping-Linköping area. Fig. 7 presents boxplots of nighttime UHI intensity for June–August 2022, compared with local station observations and EOBS27. The SURFEX 300 m simulation results align more closely with station-based observations across most stations, whereas HCLIM12 and EOBS27 tend to underestimate UHI intensity due to their lower spatial resolution. These results further demonstrate the benefits of using high-resolution simulations to accurately represent UHIs.

The UHI effects are notably prominent in the Stockholm region, where UHI in EOBS27 is as high as 3 °C, while UHI in model simulations is as high as 5 °C (Fig. 6). In the Norrköping-Linköping area, the UHI magnitudes are lower than those over Stockholm, typically varying around 0 °C for EOBS27, while model simulations ranges from 0.5 °C to 3 °C. It should be mentioned that other studies (e.g., Opach et al., 2020) have observed a positive UHI intensity in the Norrköping area, consistent with the model simulations. One potential explanation for the lower UHI over Norrköping-Linköping compared to Stockholm might be the much smaller urban area of the former, which, in line with previous research on the relationship between the UHI intensity and the physical size of the city (e.g.

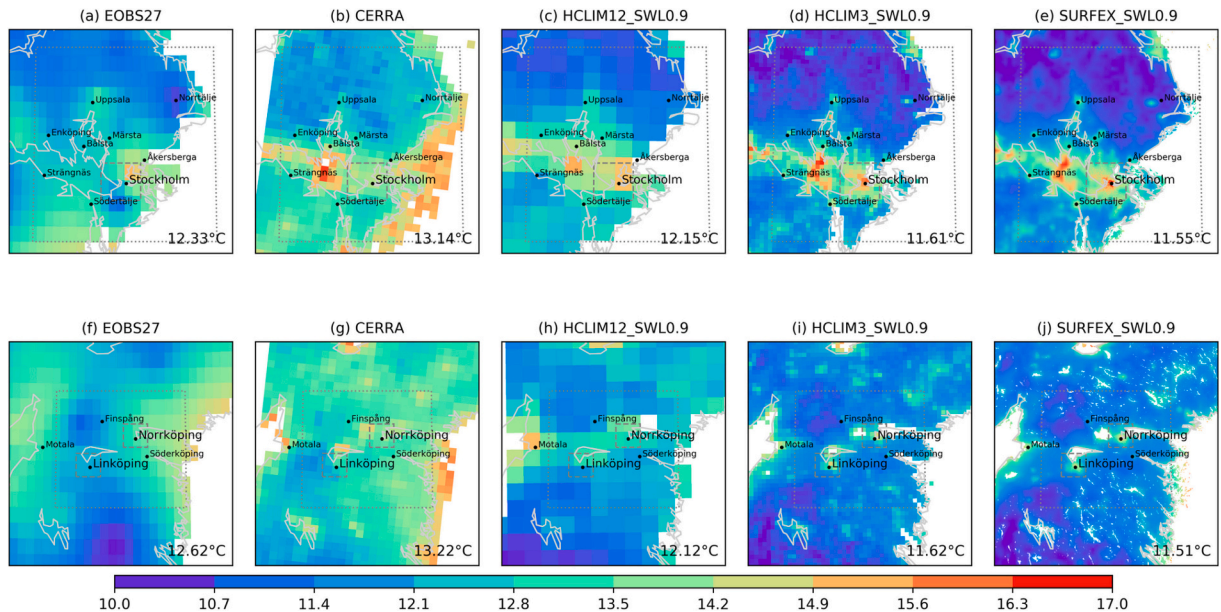


Fig. 4. The maps of daily minimum T_{2m} (°C) across the Stockholm (a-e) and Norrköping-Linköping (f-j) domain for EV3 (2018) averaged over the JJA period in EOBS27, CERRA, HCLIM43-AROME 12 km, HCLIM43-AROME 3 km, and SURFEX 300 m simulations. Note that the daily minimum T_{2m} of CERRA reanalysis is obtained from 3-hourly data due to data availability limitations.

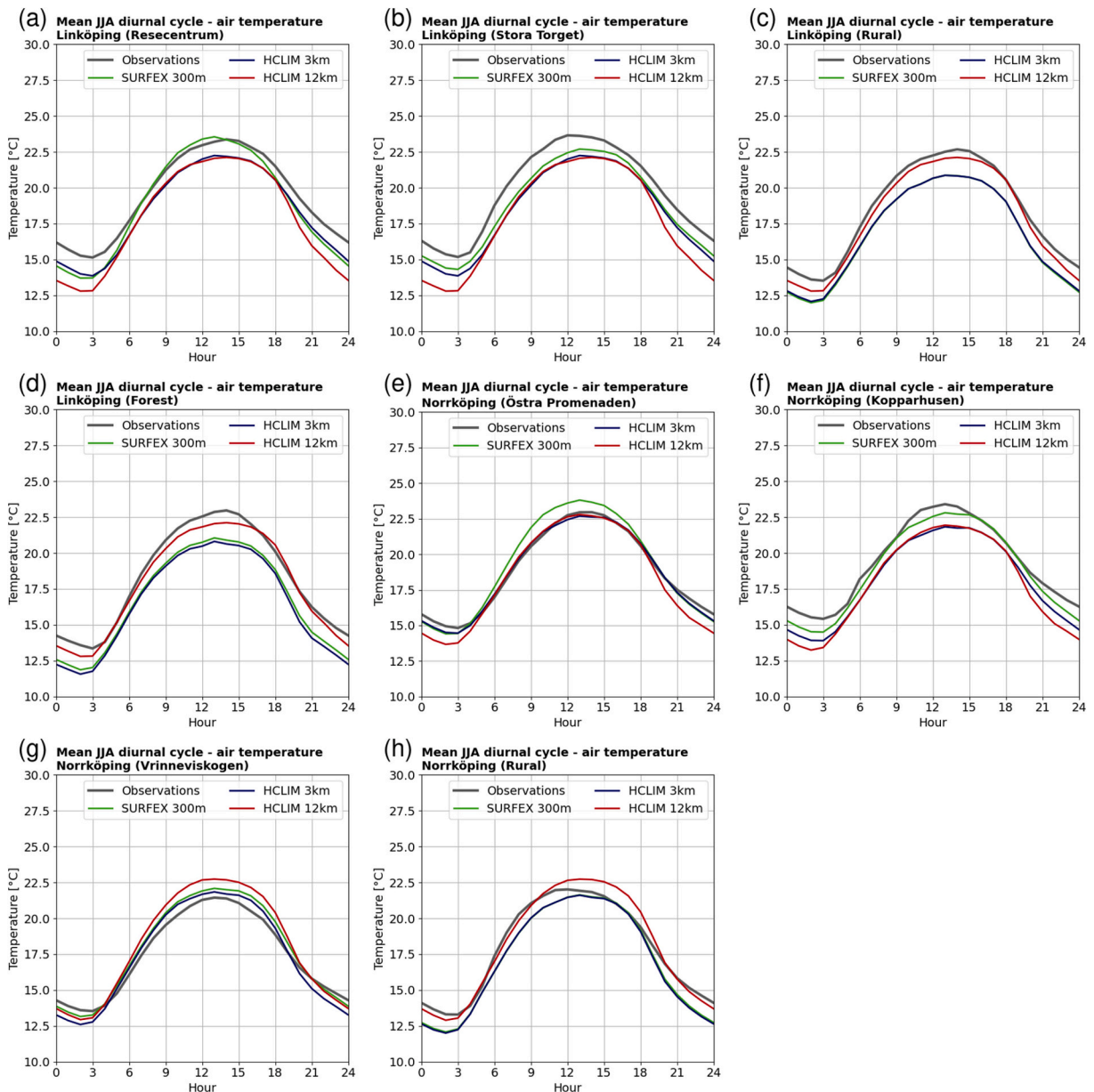


Fig. 5. The diurnal cycles of T_{2m} from model simulations (HCLIM43-AROME at 12 km in red, HCLIM43-AROME at 3 km in blue, and SURFEX at 300 m in green) compared to observations from several stations in urban and rural areas, averaged over June–August 2022 in the Norrköping–Linköping region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Ramamurthy and Bou-Zeid, 2017), may result in a reduced temperature gradient between urban and rural areas.

3.2. Future changes

3.2.1. Future change of daily 2-m air temperature

In general, the future changes of daily mean T_{2m} simulated by HCLIM43-AROME at 3 km and SURFEX at 300 m show similar results, while the results of HCLIM43-AROME at 12 km are slightly different, with a small difference of less than 0.2 °C (Fig. 8). Specifically, over Stockholm, the change of daily mean T_{2m} from the three simulations under SWL2 compared to SWL0.9 are 1.64 °C–1.69 °C, 1.37 °C–1.56 °C and 1.49 °C–1.65 °C for EV1, EV2 and EV3, respectively. Under SWL3, the corresponding changes compared to SWL0.9 are 2.70 °C–2.72 °C, 2.62 °C–2.80 °C and 2.72 °C–2.85 °C. Similar magnitudes are observed in the changes of daily T_{2m} over Norrköping–Linköping. All these changes are higher than the global mean change for SWL2 (2 °C) and SWL3 (3 °C), which are 1.1 °C and 2.1 °C higher compared to SWL0.9 (0.9 °C), respectively. This is consistent with the expected trend of amplified warming over northern high

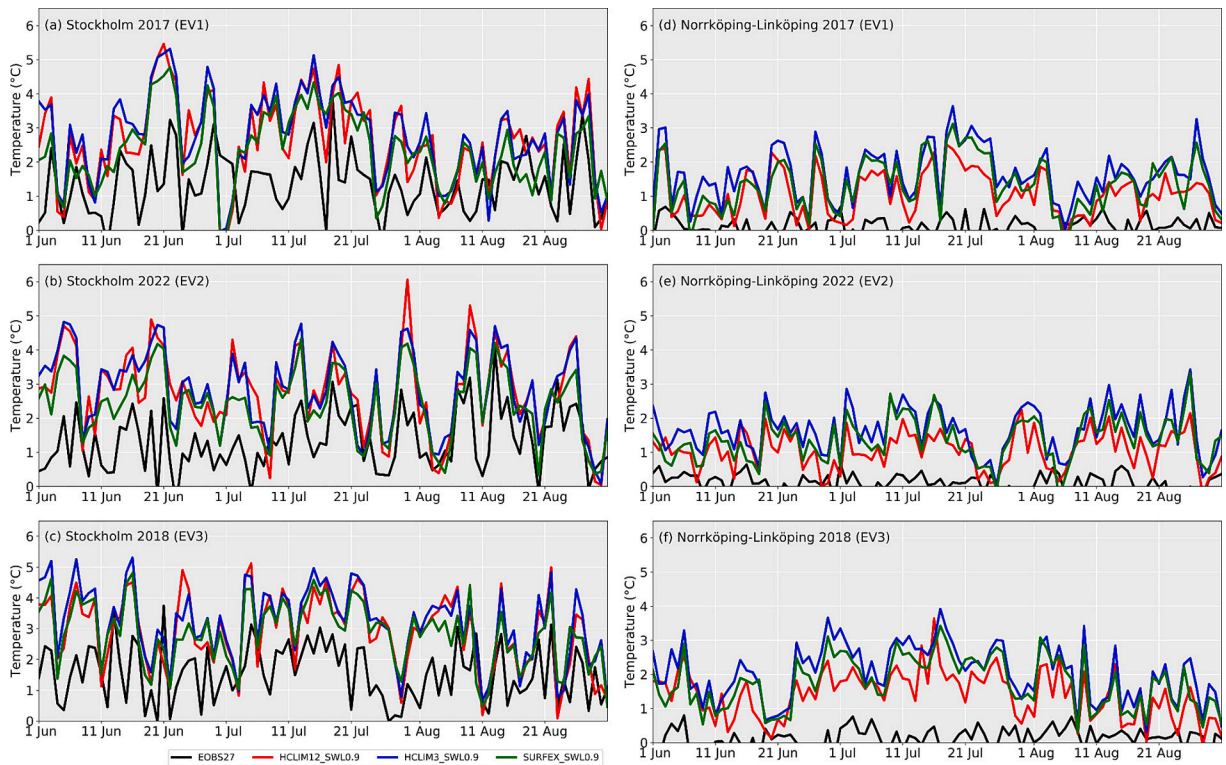


Fig. 6. Same as Fig. 3 but for the UHI intensity, calculated as the difference between daily minimum T_{2m} (°C) in urban and rural areas.

latitudes in nearly all seasons compared to the global mean (Lee et al., 2021; Gutiérrez et al., 2021). It is noteworthy that the changes in daily minimum T_{2m} exceed those in daily mean and daily maximum values. This result suggests that climate warming during nighttime is more pronounced than during the daytime over the study domain. This asymmetric diurnal temperature change aligns with other studies (e.g., Doan et al., 2022; Katavoutas et al., 2023). The detailed spatial distribution of T_{2m} changes is provided in Fig. A6, based on SURFEX simulations.

3.2.2. Future change of UHI intensity

Fig. 9 illustrates the relationship between ΔT_u and ΔT_r for EV2 under SWL2 and SWL3 in comparison to SWL0.9 across the Stockholm domain. The ΔT_u and ΔT_r denote mean values calculated day by day (i.e. June 1st of SWL2 vs June 1st of SWL0.9) between 00:00 and 03:00, averaged over urban and rural areas, respectively, resulting in a total of 92 points (i.e., the number of days from June to August). In most cases, both ΔT_u and ΔT_r exhibit positive values, indicating temperature increases over both urban and rural regions, with a higher increase observed under SWL3 than SWL2. The majority of slopes are below 1.0, although some are not statistically significant. These results indicate that the rise in T_u is proportionally lower than the increase in T_r . Consequently, this results in a decreased UHI under SWL2 and SWL3 (the UHI phenomenon still exists) compared to SWL0.9. Similar trends are observed for EV1 and EV3 over Stockholm for HCLIM12 and HCLIM3 (Fig. 9g). Over the Norrköping-Linköping domain, the slopes vary around 1.0, and lack statistical significance (Fig. 9h), suggesting no significant changes in the UHI intensity in the future warmer climate.

Our findings indicating a decreased UHI effect under climate change align with the results reported by Lind et al. (2022) and Scott et al. (2018). Lind et al. (2022) performed a comprehensive analysis of HCLIM38-AROME simulations covering the periods 1986–2005, 2041–2060, and 2081–2100, revealing a consistent decrease in the UHI intensity over Copenhagen, Helsinki, Oslo, and Stockholm during the summer nights. Scott et al. (2018) examined daily minimum air temperatures observed across 54 US cities from 2000 to 2015, suggesting a reduction in UHI intensity under warmer conditions. They associated the UHI reduction with an increase in humidity, as the nights with lowest UHI intensity occur during moist conditions. In dry conditions, rural areas release heat more effectively through radiative cooling at night compared to urban areas, where dense infrastructure retains more heat. When humidity increases, moisture in rural areas trapping outgoing longwave radiation and slowing down radiative cooling. This results in a higher rural temperature and decreased UHI intensity. Lauwaet et al. (2016) and Keat et al. (2021) found that the different heat capacity over urban and rural areas can explain higher increase of nighttime temperatures in rural areas compared to urban areas with increased incoming longwave radiation. It should be noted that the physiography, urbanization and greenhouse gases are static in our study, with no urban expansion or climate adaptation considered. While this simplification affects the results of this study, particularly at the local level, our findings suggest that rural areas may experience faster warming than urban areas under global warming, assuming that no changes would have occurred in urbanization and greenhouse gases emissions.

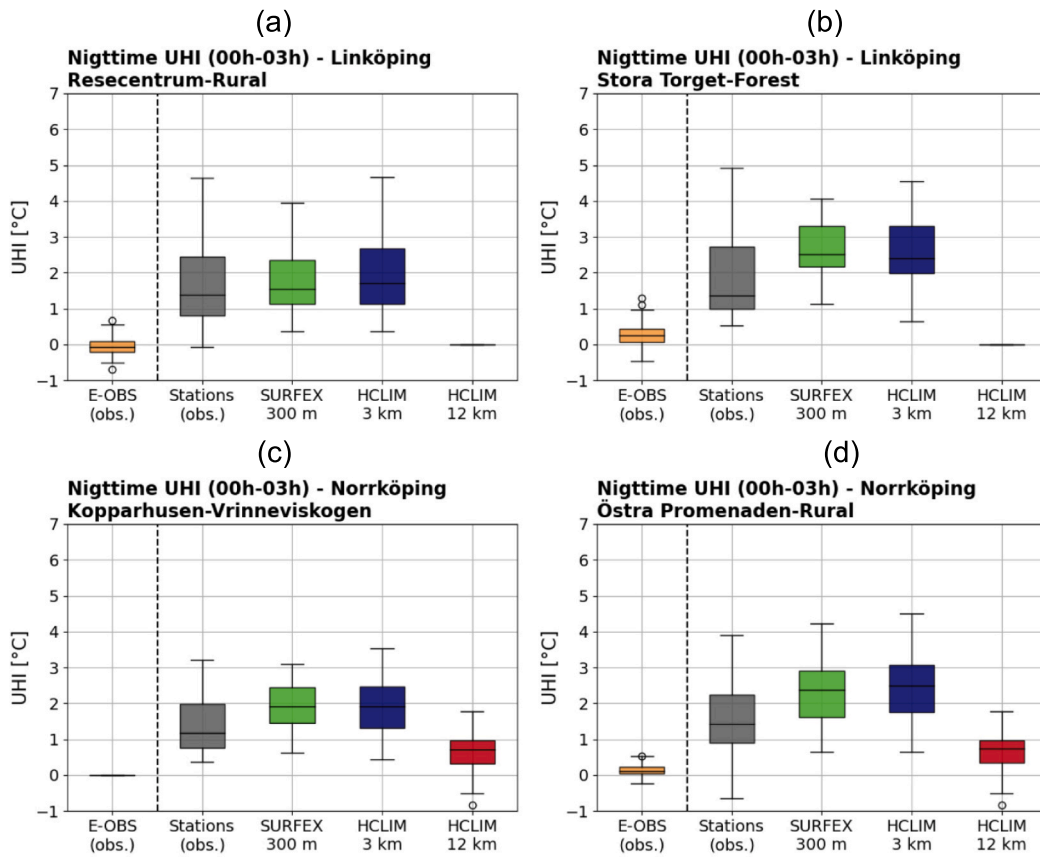


Fig. 7. Boxplot of nighttime (00:00–03:00) UHI intensity ($^{\circ}\text{C}$) for June–August 2022, comparing E-OBS (orange), station-based observations (gray), and model simulations: SURFEX at 300 m (green), HCLIM at 3 km (blue) and HCLIM at 12 km (red). The box represents the range from the 25th to the 75th percentile, while the horizontal line inside the box indicates the median. The whiskers extend from the box to the most distant data points within 1.5 times the interquartile range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

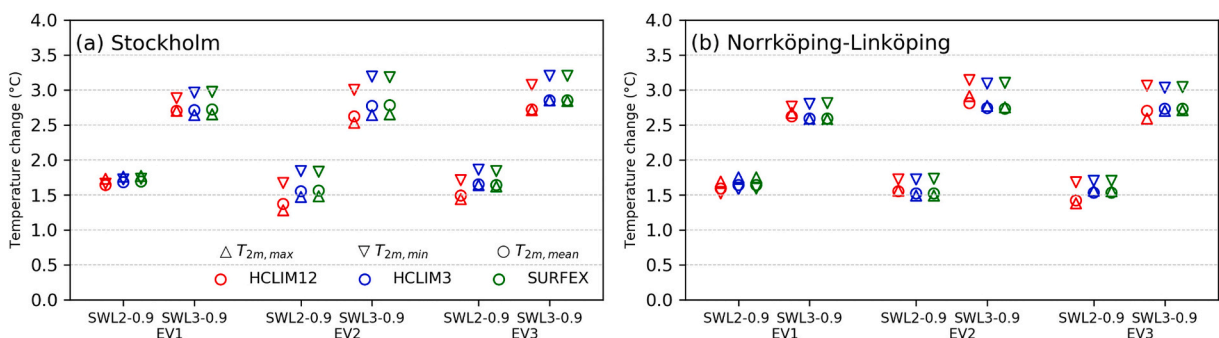


Fig. 8. The change of domain averaged daily maximum ($T_{2m,max}$), daily minimum ($T_{2m,min}$) and daily mean ($T_{2m,mean}$) T_{2m} under SWL2 and SWL3 in comparison to SWL0.9 over Stockholm (a) and Norrköping-Linköping (b) domain.

3.3. Synergies between UHI and heat waves

3.3.1. The relationship between UHI and atmospheric variables

To understand the factors contributing to future changes in UHI intensity, this section aims to examine the relationship between UHI and diverse variables within the model simulations. The heatmaps presented in Fig. 10 illustrate the correlation coefficients between the UHI intensity averaged during night time (00:00–03:00) over the summer (JJA) and various variables across different

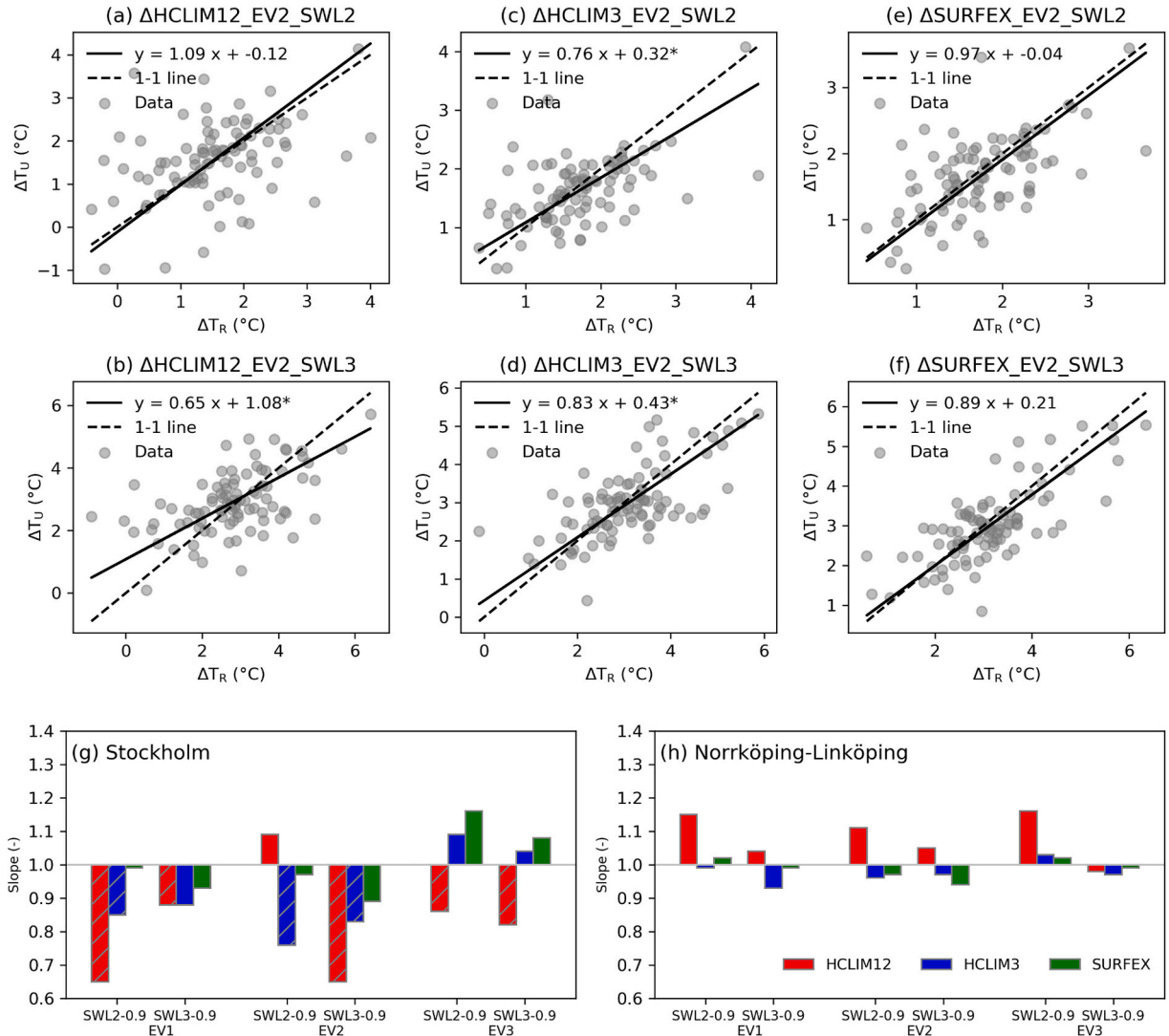


Fig. 9. The change of T_{2m} at 00:00–03:00 local time average over urban versus over rural area during JJA for Stockholm region under SWL2 (a, c, e) and SWL3 (b, d, f) simulated by HCLIM43-AROME 12 km (a, b), HCLIM43-AROME 3 km (c, d) and SURFEX 300 m (e, f) for EV2. The solid line shows the total least squares fit to the data with slope m , and the dashed line shows the 1–1 line. The statistical significant slope values are indicated by a symbol * at the end of each equation. The slopes of total least squares for all events and model results are summarized in (g) and (h) with the striped bars representing statistically significant results based on a t -test (p -value ≤ 0.05).

regions, models and SWLs. Note that correlations are not presented for all variables in the SURFEX 300 m configuration, as these variables are not utilized in the SURFEX offline simulations. For each SWL, the values from the three events (EV1, EV2 and EV3) are considered, resulting in the calculation of each correlation coefficient based on 276 values. All correlation coefficients in Fig. 10 are statistically significant at p -value lower than 0.05 using t -test. Generally, UHI displays positive correlations with daily mean values of surface downward short-wave radiation (correlation ranging from 0.30 to 0.48, Fig. 10a), surface net radiation (correlation ranging from 0.24 to 0.45, Fig. 10c), sensible heat flux (correlation ranging from 0.39 to 0.57, Fig. 10d), and sea level pressure (correlation ranging from 0.29 to 0.47, Fig. 10g). We also separated the downward shortwave radiation and net longwave radiation at the surface into daytime (15:00–18:00) and nighttime (00:00–03:00) intervals, and found that the conclusions remain consistent between these periods and with those based on daily mean values. The positive correlation between UHI and surface energy balance variables can be explained by the higher heat capacity of cities compared to rural areas (e.g., Lauwaet et al., 2016). In SURFEX v8.1, the volumetric heat capacity is in the order of magnitude of $10^6 \text{ J m}^{-3} \text{ K}^{-1}$ for urban (Masson, 2000) and $10^5 \text{ J m}^{-3} \text{ K}^{-1}$ for green canopy (Boone et al., 2017). Subsequently, during nighttime, the accumulated heat is released, leading to higher temperatures over the town compared to rural areas, thus contributing to a higher UHI during the night.

In contrast, night time UHI exhibits a negative correlation with daily average net long-wave radiation at surface (correlation ranging from -0.40 to -0.51 , Fig. 10b), nighttime 10 m wind speed (correlation ranging from -0.46 to -0.63 , Fig. 10e), daily average

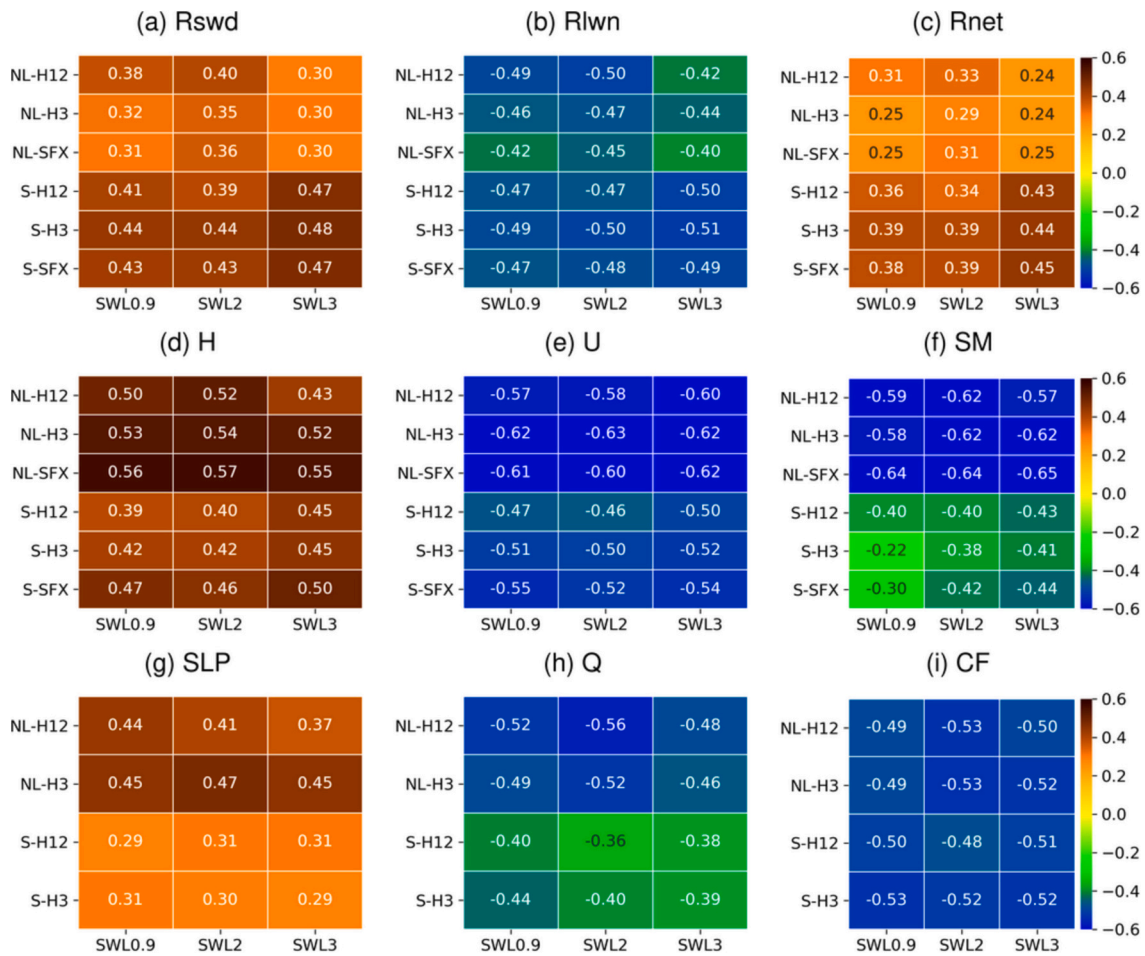


Fig. 10. The heatmap of correlation coefficients between UHI at nighttime (00:00–03:00) and different variables: surface downward short-wave radiation (R_{swd}), surface net long-wave radiation (R_{lwn}), surface net radiation (R_{net}), sensible heat flux (H), 10 m wind speed (U), surface soil moisture for open land (SM), sea level pressure (SLP), moisture flux at 850 hPa (Q), low cloud fraction (CF). On the y-axis, NL, S, H12, H3 and SFX represent Norrköping-Linköping, Stockholm, HCLIM43-AROME at 12 km, HCLIM43-AROME at 3 km and SURFEX 300 m, respectively.

cloud fraction (correlation ranging from -0.48 to -0.53 Fig. 10i), daily average soil moisture (correlation ranging from -0.22 to -0.64 , Fig. 10f) and daily average moisture flux at 850 hPa (correlation ranging from -0.36 to -0.56 , Fig. 10h). Low wind speeds are indicative of diminished advective cooling by low-temperature air from surrounding rural areas, consequently intensifying the UHI effect (Li and Bou-Zeid, 2013). Low wind speed and decreased cloud cover imply increased atmospheric stability and reduced radiative and turbulent exchanges in and around the urban region, contributing to a stronger UHI intensity (Oke, 1982; Morris et al., 2001; Wang et al., 2021). Fischer et al. (2012) pointed out that the nocturnal UHI is most pronounced under clear-sky conditions, but it is reduced in cloudy conditions as clouds dampen the radiative cooling differences between rural and urban areas. In drier conditions, the city primarily covered with impervious surfaces tends to act as a source region for sensible heat due to low evaporation limited by soil moisture, further amplifying the UHI intensity (Oke, 1982; Li and Bou-Zeid, 2013). While UHI also exhibits a negative correlation with latent heat flux and specific humidity, the correlation coefficients are low, and many values are not statistically significant (not shown).

The correlations appear to be independent of the models and warming levels but vary across different variables and regions. For instance, sensible heat flux, 10 m wind speed, surface soil moisture over open land, sea level pressure, and moisture flux at 850 hPa tend to show stronger correlations over Norrköping-Linköping compared to Stockholm. Conversely, surface downward shortwave radiation and surface net radiation exhibit higher correlations over Stockholm than over Norrköping-Linköping.

The variables used to calculate correlations with UHI in Fig. 10 are averaged over all land grid points, excluding lake and sea tiles. We also calculated the correlation coefficients by averaging the variables over urban and rural areas separately. The results indicate that the correlation coefficients remain largely consistent with those obtained using all land grid points within the domain.

3.3.2. The response of UHI intensity to heat waves

The response of the UHI to heat waves remains a critical unanswered question (e.g., Scott et al., 2018; Richard et al., 2021; Kong et al., 2021; Kabisch et al., 2023). Moreover, there is still insufficient understanding of the processes that govern the UHI response to

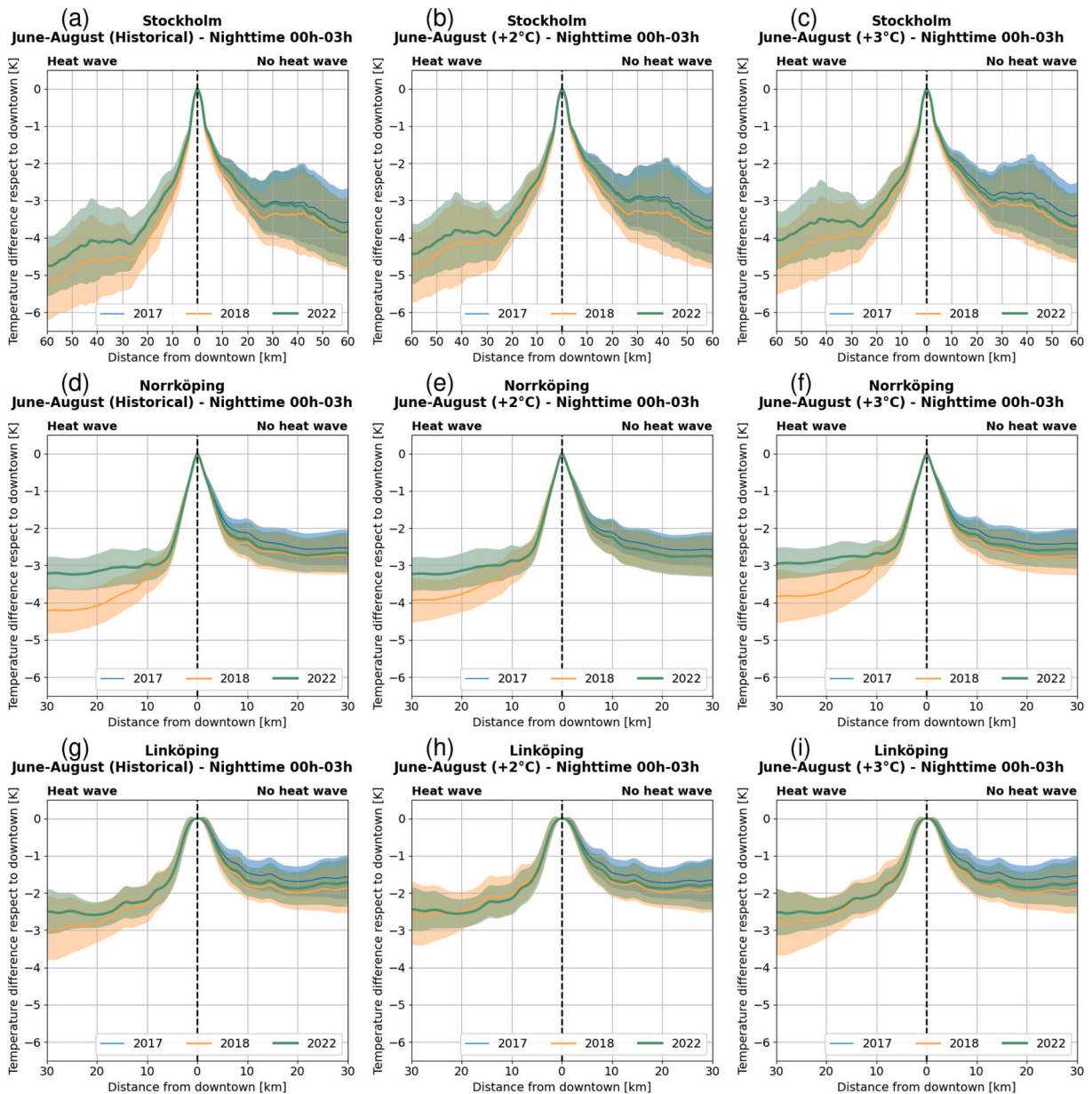


Fig. 11. The 2-m air temperature difference at varying distances from the city center under heat wave (left panel) and non-heat wave periods (right panel) during nighttime (00:00–3:00). The data is from SURFEX 300 m simulations under SWL0.9 (a, d, g), SWL2 (b, e, h) and SWL3 (c, f, i) for Stockholm (a, b, c), Norrköping (d, e, f) and Linköping areas (g, h, i). The shaded areas indicate the standard deviation of the 2-m air temperature, providing a measure of spatial variability.

heat waves across various regions and climates. In pursuit of understanding these questions, we categorize days into those with heat waves and those without, over the June–August period for the summers with heat waves, EV2 (2022) and EV3 (2018). Heat wave days are defined as those wherein the domain-averaged daily maximum temperature surpasses 25 °C for at least five consecutive days - the commonly used definition of heat waves in Sweden. This results in 15, 20, and 27 heatwave days for EV2 and 22, 30, and 37 for EV3 under SWL0.9, SWL2, and SWL3 over Stockholm. For Norrköping–Linköping, the counts are 15, 19, and 28 for EV2 and 26, 34, and 34 for EV3. Fig. 11 illustrates the variations in T_{2m} during nighttime (00:00–03:00) during heat wave and non-heat wave periods, relative to the distance from the city center across the three cities and under the three selected SWLs. The y-axis values are computed by averaging all T_{2m} differences within a circular region centered on the city center, with the distance to the city center as the radius. To elucidate the changing details, we chose the SURFEX simulation at 300 m.

The temperature gradient from the urban center to the surrounding rural areas can be as high as -5 °C/60 km during night time (Fig. 11a), while it is around -2 °C/60 km during day time (not shown) for SWL0.9 in Stockholm. This effect is due to the high heat

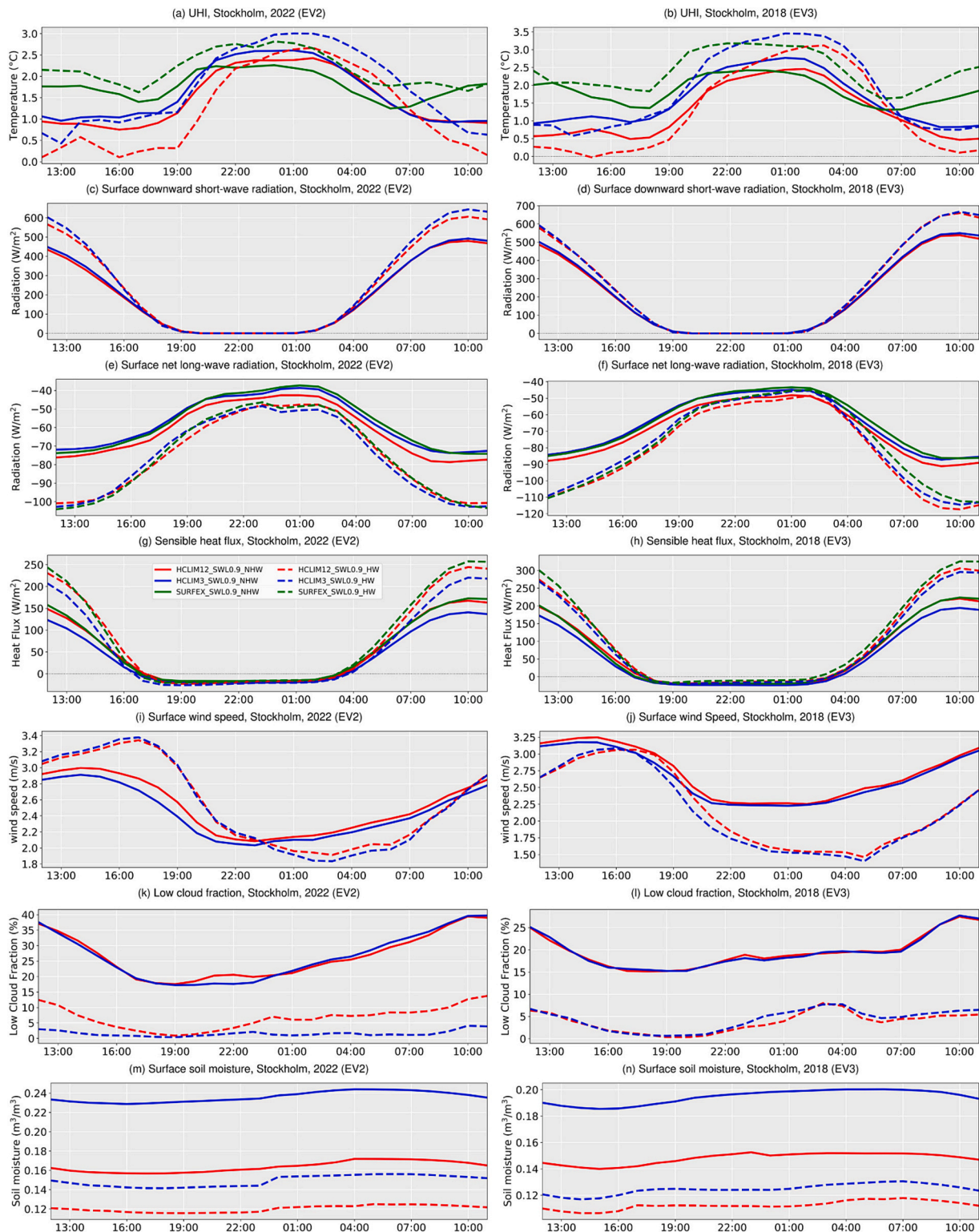


Fig. 12. The diurnal cycle of UHI intensity (a, b), downward short-wave radiation at the surface (c, d), net long-wave radiation at the surface (e, f), sensible heat flux (g, h), 10 m wind speed (i, j), low cloud fraction (k, l), and surface soil moisture for open land (m, n) averaged over Stockholm domain for EV2 and EV3 under SWL0.9, distinguished between the heat wave (dashed lines) and non-heat wave periods (solid lines).

storage capacity of concrete and cement buildings over urban areas, which have low albedo and retain heat. After sunset, these surfaces release heat gradually, keeping the air warmer and intensifying the nocturnal UHI (e.g., Giridharan et al., 2005; Oke et al., 2017; Amorim et al., 2020). Compared to Stockholm region (around 60 km including surrounding areas), the temperature variation is lower for Norrköping and Linköping areas as their city size is smaller (around 30 km including surrounding areas). The temperature variation becomes relatively small at about 7–8 km from the center of Norrköping/Linköping, attributed to their compact urban layout surrounded by forest and cropland. In contrast, Stockholm shows temperature variations extending up to 60 km, influenced by the UHI effect contributed by neighboring satellite cities. These findings underscore the significant role of city size in shaping UHI characteristics. Generally, the temperature gradients during heat wave periods are consistently steeper when compared to non-heat wave periods across all cases. For the example of Stockholm, the temperature variation gradient can be as high as $-4^{\circ}\text{C}/60\text{ km}$ to $-5^{\circ}\text{C}/60\text{ km}$ for heat wave period, but it is around $-3^{\circ}\text{C}/60\text{ km}$ to $-4^{\circ}\text{C}/60\text{ km}$ for non-heat wave periods during night time (Figs. 11a–11c). The higher gradients indicate a stronger UHI effect during heat wave events. Specifically, the magnitude of the gradient is more pronounced for EV3 (2018) than for EV2 (2022) during heat waves for all cities, aligning with the expectation that EV3 is more extreme than EV2. Throughout non-heat wave periods, all cases exhibit a consistent magnitude of gradients (around -4°C , -2.5°C and -2°C , at the edge of Stockholm, Norrköping and Linköping, respectively).

To further understand the reason behind the higher gradient during heat wave events, we compare the diurnal cycles of UHI intensity and related variables between heat wave and non-heat wave periods (Figs. 12 and A16). There is consistently higher UHI intensity during nighttime over the heat wave periods compared to non-heat wave periods (Figs. 12a–12b, A16a–A16b). Specifically, during the heat wave events, the downward short-wave radiation at the surface exceeds that of non-heat wave periods by approximately 100 W/m^2 during the daytime (Figs. 12c–12d, A16c–A16d). The net radiation at the surface (not shown) and sensible heat flux exhibit consistent variations with downward short-wave radiation, resulting in intensified heating over the town during the day (Figs. 12g–12h, A16g–A16h). During heat waves, the nighttime 10 m wind speed, low cloud fraction and soil moisture exhibit lower values compared to periods without heat waves, which further intensify the UHI effect (Figs. 12i–12n, A16i–A16n). These findings are

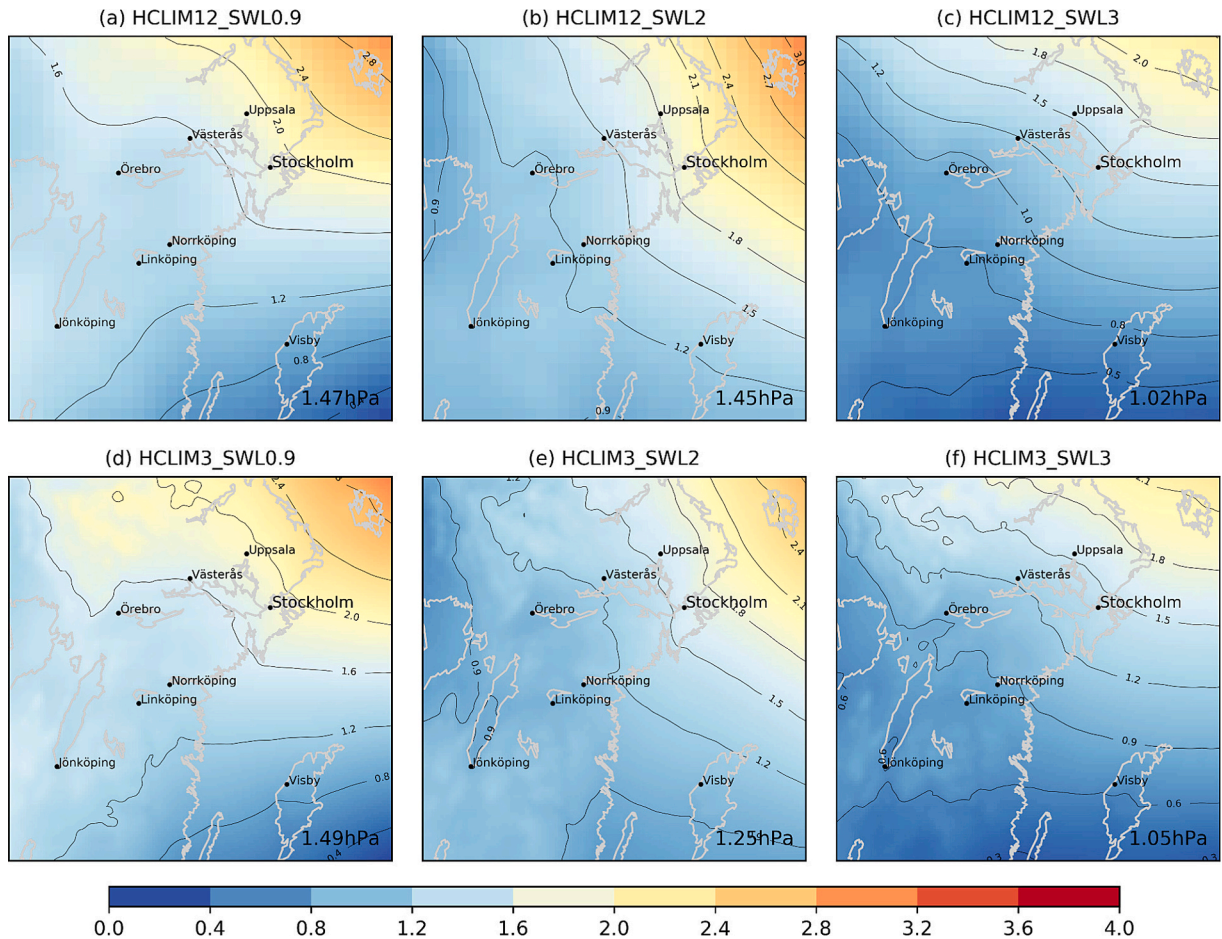


Fig. 13. Spatial distribution of the difference in sea level pressure (unit: hPa) between heat wave and non-heat wave periods during the summer months (June–August) of EV3 (2018) for HCLIM43-AROME simulations at 12 km (a–c), and 3 km (d–f). Columns represent different warming levels: SWL0.9 (left), SWL2 (middle), and SWL3 (right).

robust since the results across HCLIM43-AROME simulations at 12 km and 3 km resolutions, as well as SURFEX offline simulations at 300 m are consistent. Additionally, the interactions between UHI and heat waves appear consistent across future climate scenarios (e. g., SWL3 in Fig. A17). When T_{2m} over town tile was used to compute UHI intensity, the synergistic relationship between UHI and heat waves remained unchanged, although the absolute value of UHI intensity was higher compared to that calculated from T_{2m} (Fig. A18).

To examine the effects of large-scale atmospheric circulations on UHI and heat wave development, we analyzed June to August days with and without heat waves, specifically examining EV2 (2022) and EV3 (2018) in Figs. 13 and A7–A11. We find that sea level pressure is higher during heat wave days compared to non-heat wave days (Figs. 13 and A11). This aligns with prior findings that the summer of 2018 over northern Europe and around 80 % of summer heatwaves in northern Europe are linked to atmospheric blocking situations (Pfahl and Wernli, 2017; Sinclair et al., 2019), which results in increased solar radiation due to anomalously clear skies. This mechanism also explains the high short-wave radiation and reduced cloud cover during heat wave periods, as shown in Figs. 12, A16 and A17. We further analyzed water vapor transport at 850 hPa for heat wave versus non-heat wave periods (Figs. A12–A15). Overall, water vapor is lower during heat waves than non-heat wave periods. Increased humidity during non-heat wave periods can limit nighttime cooling by trapping outgoing longwave radiation, which in turn tends to intensify the nighttime UHI effect (see Fig. 10).

We further excluded days with precipitation over 1 mm/day to minimize the effects of precipitation. The relationship depicted in Fig. 10 remains consistent even after excluding the precipitation days. Fig. 14 shows the diurnal cycles of UHI intensity and related variables between heat wave and non-heat wave periods during the historical period (SWL0.9) after excluding the precipitation days. For EV3 in 2018, the UHI intensity over heat waves was higher than during non heat wave periods (Fig. 14b), attributed mainly to higher sensible heat flux and lower wind speeds (Figs. 14d and f), while other variables (downward short-wave radiation, low cloud fraction, surface soil moisture) showed minimal change. In contrast, for EV2 in 2022, UHI intensity remained unchanged or slightly lower during nighttime heat waves compared to non-heat wave periods (Fig. 14a), with minimal changes in short-wave radiation, sensible heat fluxes (Fig. 14c), surface wind speed (Fig. 14e), surface soil moisture and low cloud fractions (not shown).

The synergistic interaction between UHI intensity and heat waves aligns with the previous study by Li and Bou-Zeid (2013), who reported a similar UHI amplification during heat wave period over the Baltimore–Washington metropolitan area, using observations and WRF simulations. Using historical observations, Schatz and Kucharik (2015) also concluded that UHIs exhibit increased intensity during extreme heat episodes, attributing this phenomenon to hot days coinciding with weather conditions favorable to strong UHIs.

3.3.3. Factors contributing to future change of UHI intensity

In section 3.2.2, we find a decreased UHI effect under future warming levels. Here, we analyze the specific climatic factors contributing to this reduction in UHI intensity using the relationships established in Fig. 10. The correlation between Δ UHI and changes in various atmospheric variables demonstrate which variations contribute most to the projected future change in UHI intensity (Fig. A19). Results indicate that surface downward short-wave radiation, net surface radiation, and sensible heat flux show positive correlations with Δ UHI under climate change, suggesting they amplify future UHI intensity. In contrast, surface net long-wave radiation, surface soil moisture, low cloud fraction, and moisture flux at 850 hPa are negatively correlated with Δ UHI, indicating a dampening effect. Sea level pressure, however, shows no correlation with Δ UHI under climate change.

4. Conclusions

This study explores the future change in summer heat waves and UHI effects, as well as the interaction between UHI intensity and heat waves in southern Sweden, focusing on Stockholm and Norrköping-Linköping. The main conclusions include:

- (1) Dynamical downscaling of heat wave events in convection permitting resolution over short time periods can be done successfully and efficiently. To mitigate computational costs, instead of continuously running the resource-intensive CPRCM (HCLIM43-AROME) over continuous multi-year long time periods, we selectively simulate several discrete summers representing different climates: 2017 (average summer), 2022 (average heat wave), and 2018 (extreme heat wave). Specifically, simulations were conducted using HCLIM43-AROME at resolutions of 12 km and 3 km, and SURFEX LSM at a resolution of 300 m. The results reveal that all model simulations successfully capture variations in 2 m air temperature and UHI when compared with EOBS27 and CERRA observations/reanalysis at daily scale. Further evaluation using ground-based observations highlights the advantages of high-resolution simulations in accurately representing 2 m air temperature and UHI.
- (2) The PGW approach is suitable to simulate the selected summers in the context of future climate change. We employ the PGW approach on ERA5 data, in combination with three warming levels obtained from EC-Earth GCM: 0.9 °C (historical), 2 °C and 3 °C above pre-industrial periods. The simulated daily mean temperature changes under SWL2 and SWL3, compared to SWL0.9 over the study areas, are projected to be in the range of 1.37 °C to 1.69 °C and 2.62 °C to 2.85 °C, respectively. These changes are more pronounced during nighttime than during the daytime. Furthermore, these values surpass the global mean warming of 1.1 °C and 2.1 °C for SWL2 and SWL3, respectively. The UHI trends indicate a decreasing trend over the study areas, assuming no changes in urbanization or greenhouse gas emissions.
- (3) We find a positive correlation between UHI intensity and sea level pressure, downward short-wave radiation, net radiation, and sensible heat fluxes, while a negative correlation is identified with surface net long-wave radiation, 10 m wind speed, low cloud fraction, moisture flux, and surface soil moisture. The higher thermal inertia over urban areas compared to rural areas results in increased heat storage during higher shortwave radiation in the daytime, leading to heightened heat release during nighttime over urban regions. Low wind speed and cloud fraction are associated with increasing atmospheric stability, indicating weaker convection and advection. In drier conditions, the city tends to have lower evaporation rates than rural areas due to limited

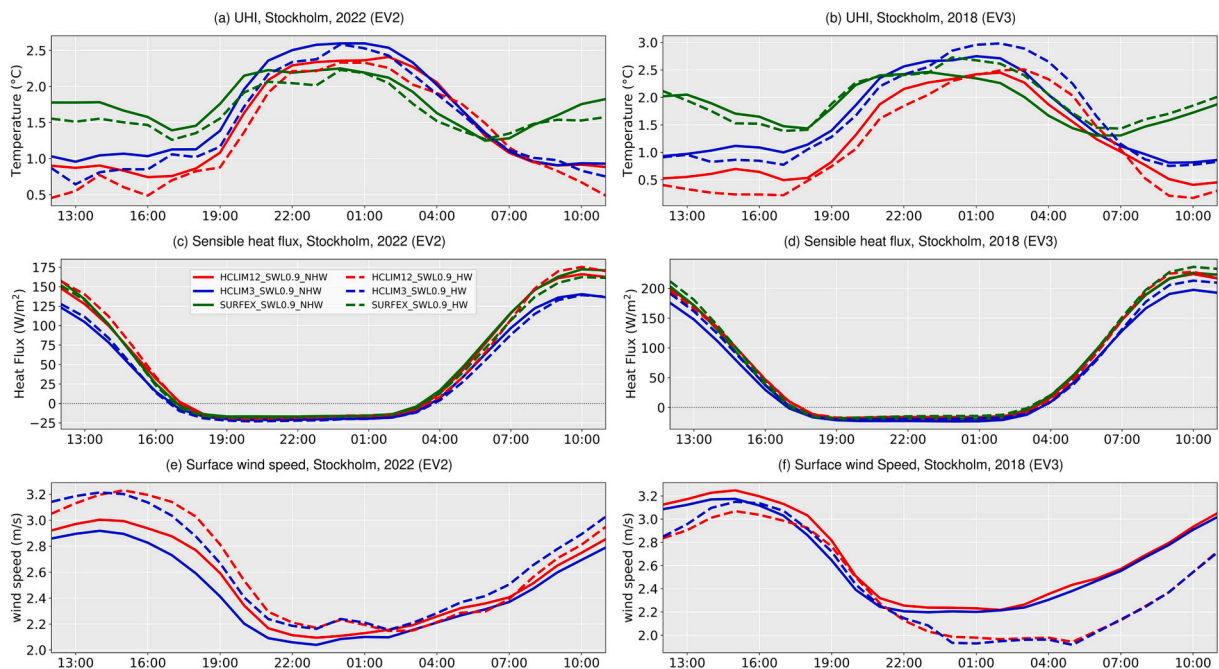


Fig. 14. Same as Fig. 12, but excluding precipitation days (> 1 mm/day).

moisture availability, further amplifying the UHI intensity. This mechanism explains the synergistic interaction between UHI intensity and heat waves. Specifically, UHI intensity amplifies during heat wave periods for EV2 and EV3 due to the higher sea level pressure, increased downward short-wave radiation, and lower wind speed, cloud fraction, soil moisture, and water vapor transport at 850 hPa when precipitation days are included. For EV2, UHI intensity remains unchanged when the precipitation days are excluded. This relationship persists under future climate scenarios SWL2 and SWL3.

The time-slice simulation approach by focusing on discrete periods, can provide higher productivity at a much lower computational cost compared to multi-year continuous simulations. This approach is applicable to other climate events such as for extreme precipitations, wildfires, and storms, etc. It is important to note that the numerical experiments conducted here, employing the PGW method, do not induce changes in the large-scale circulation pattern. Rather, these experiments should be regarded as an ‘imposed’ warming experiment and rather than a robust scenario depicting future climate, as highlighted in previous studies (Rasmussen et al., 2011; Tewari et al., 2019). Furthermore, it is essential to emphasize that the results presented here pertain to static urban conditions. With the global increase in urban population, urbanization trajectories, and increasing greenhouse gas emission, urban heat island intensity can be expected to be further enhanced. Future investigations are encouraged to incorporate dynamic changes in urban extent and properties (Amorim et al., 2020; Wang et al., 2023) for a more comprehensive understanding of changes in heat waves and UHI that may occur in the future as a result of the combination of both urban transformation and climate change. It is expected that both the HCLIM and SURFEX (in offline mode) models have inherent biases. However, based on current evaluations using local station-based observations, nighttime UHI results appear unaffected. These observations are limited to the summer of 2022 and focus only on Norrköping and Linköping. Additionally, uncertainties in CERRA reanalysis and EOBS gridded observational data highlight the need for high-quality, high-resolution observations for a comprehensive evaluation of CPRCM models over urban and surrounding rural areas.

CRedit authorship contribution statement

Fuxing Wang: Writing – review & editing, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization, Validation, Writing - original draft, Supervision. **Aitor Aldama-Campino:** Writing – review & editing, Writing - original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Danijel Belušić:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Jorge H. Amorim:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization, Project administration. **Isabel Ribeiro:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Lotten Wirén:** Writing – review & editing, Funding acquisition. **David Segersson:** Conceptualization. **Ralf Döscher:** Writing – review & editing, Funding acquisition. **Carlo Navarra:** Writing – review & editing. **Tina-Simone Neset:** Writing – review & editing, Funding acquisition. **Petter Lind:** Writing – review & editing.

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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Appendix A. Appendix

Table A1
The observation station information.

No.	Station name	City	Longitude	Latitude	Note
1	Ostra Promenaden	Norrköping	16.200	58.588	Urban
2	Kopparhusen	Norrköping	16.176	58.588	Urban
3	RuralNkpg	Norrköping	16.121	58.563	Rural
4	Vrinneviskogen	Norrköping	16.191	58.567	Rural
5	Resecentrum	Linköping	15.627	58.415	Urban
6	Stora Torget	Linköping	15.621	58.411	Urban
7	RuralLkpg	Linköping	15.737	58.417	Rural
8	Forest	Linköping	15.627	58.372	Rural

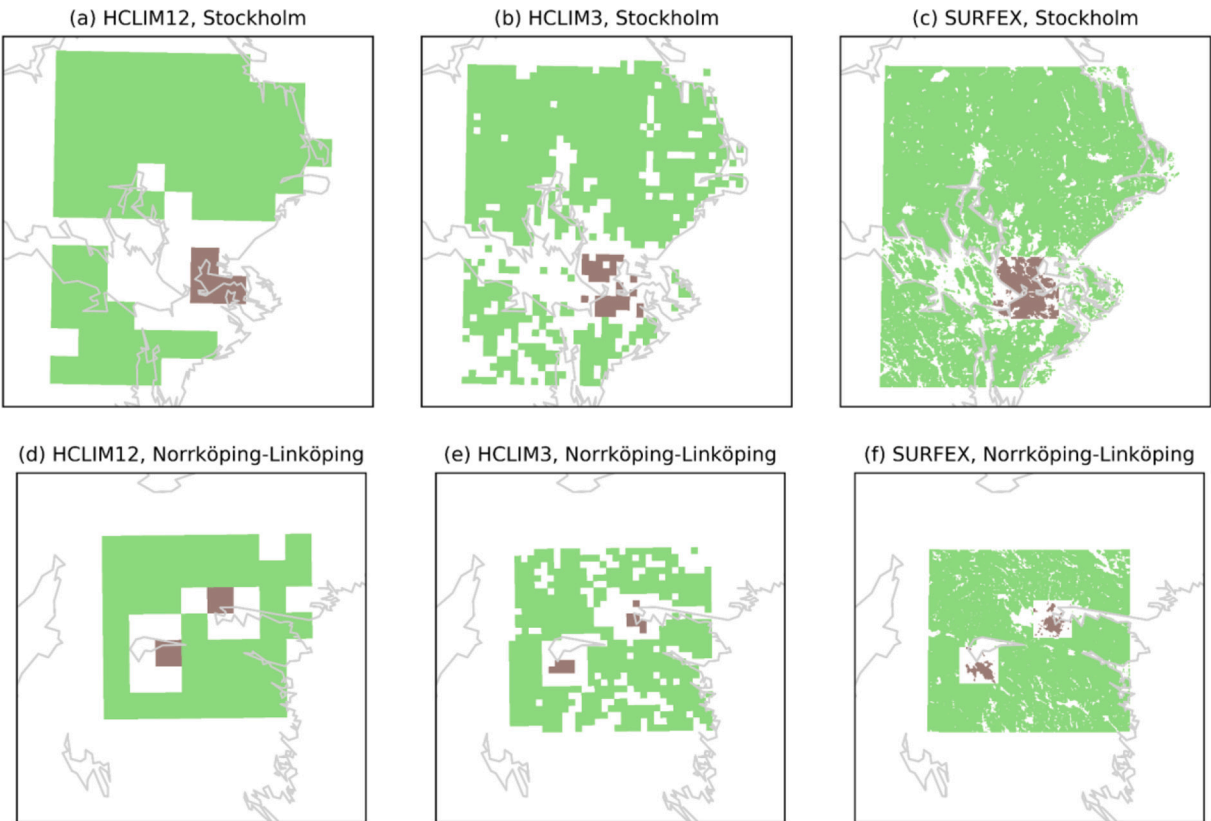


Fig. A1. The grid points used by HCLIM43-AROME 12 km, HCLIM43-AROME 3 km and SURFEX 300 m simulations for urban (brown colour) and rural (green colour) areas for computing UHI over Stockholm and Norrköping-Linköping regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

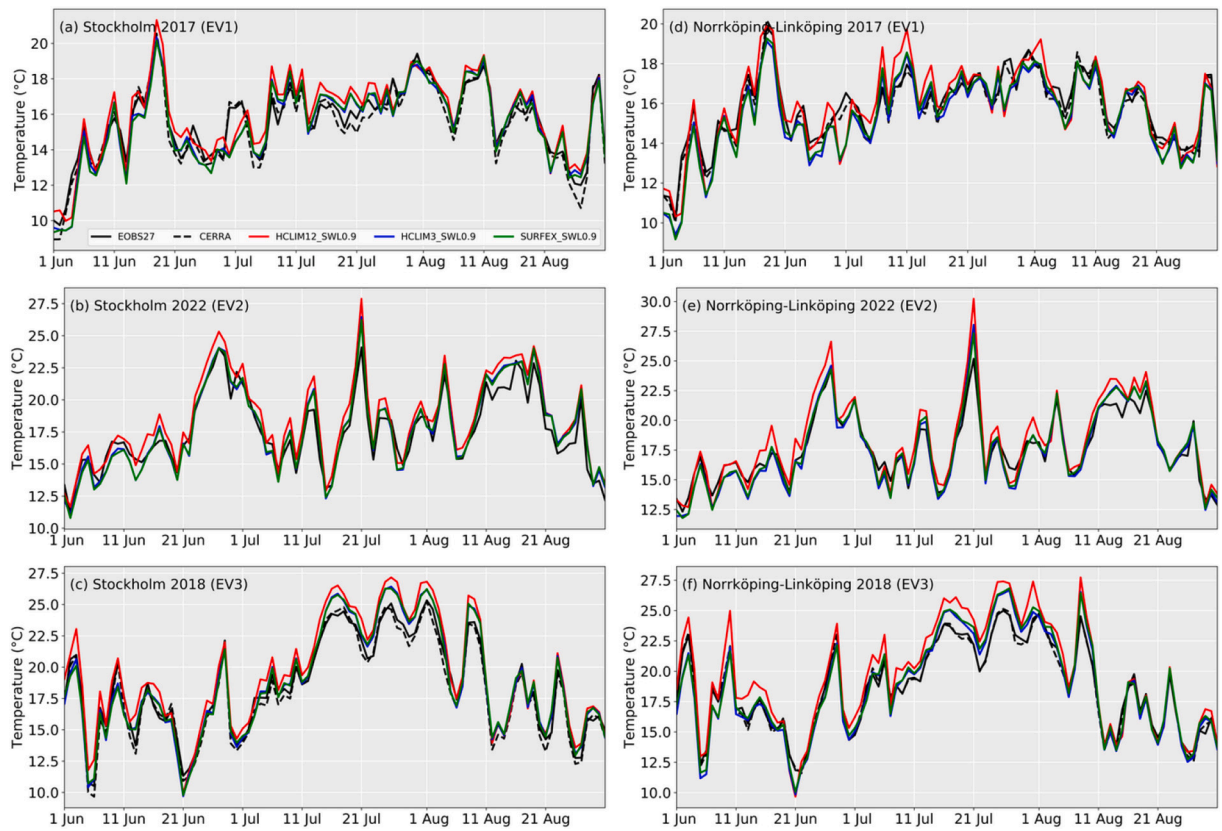


Fig. A2. Same as Fig. 3 but over urban areas.

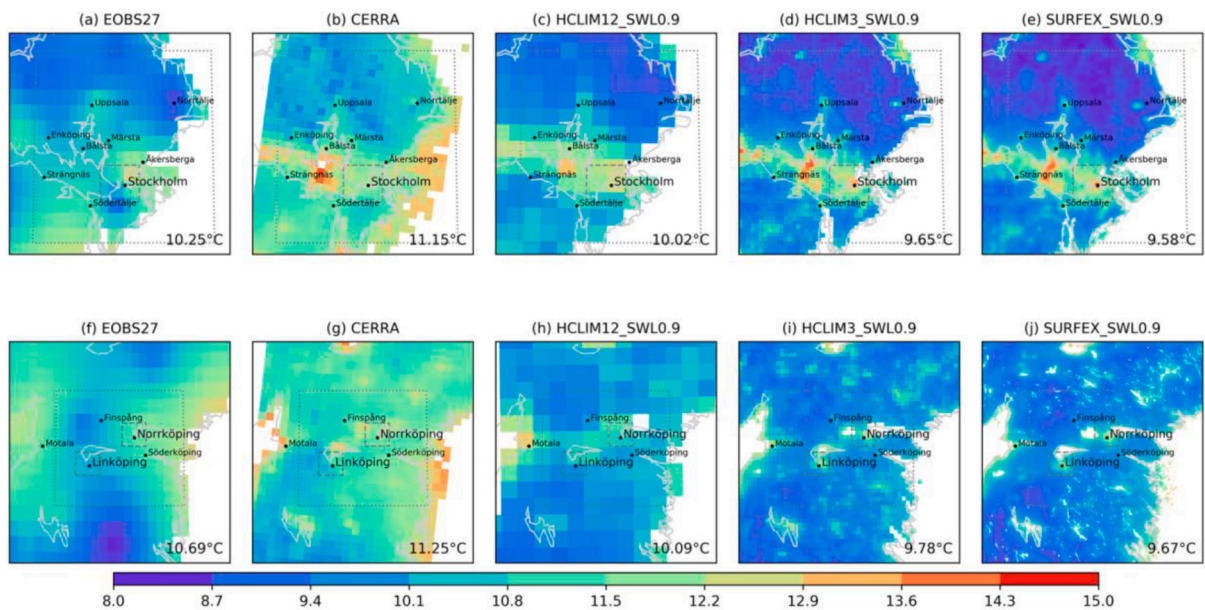


Fig. A3. Same as Fig. 4 but for EV1 in 2017.

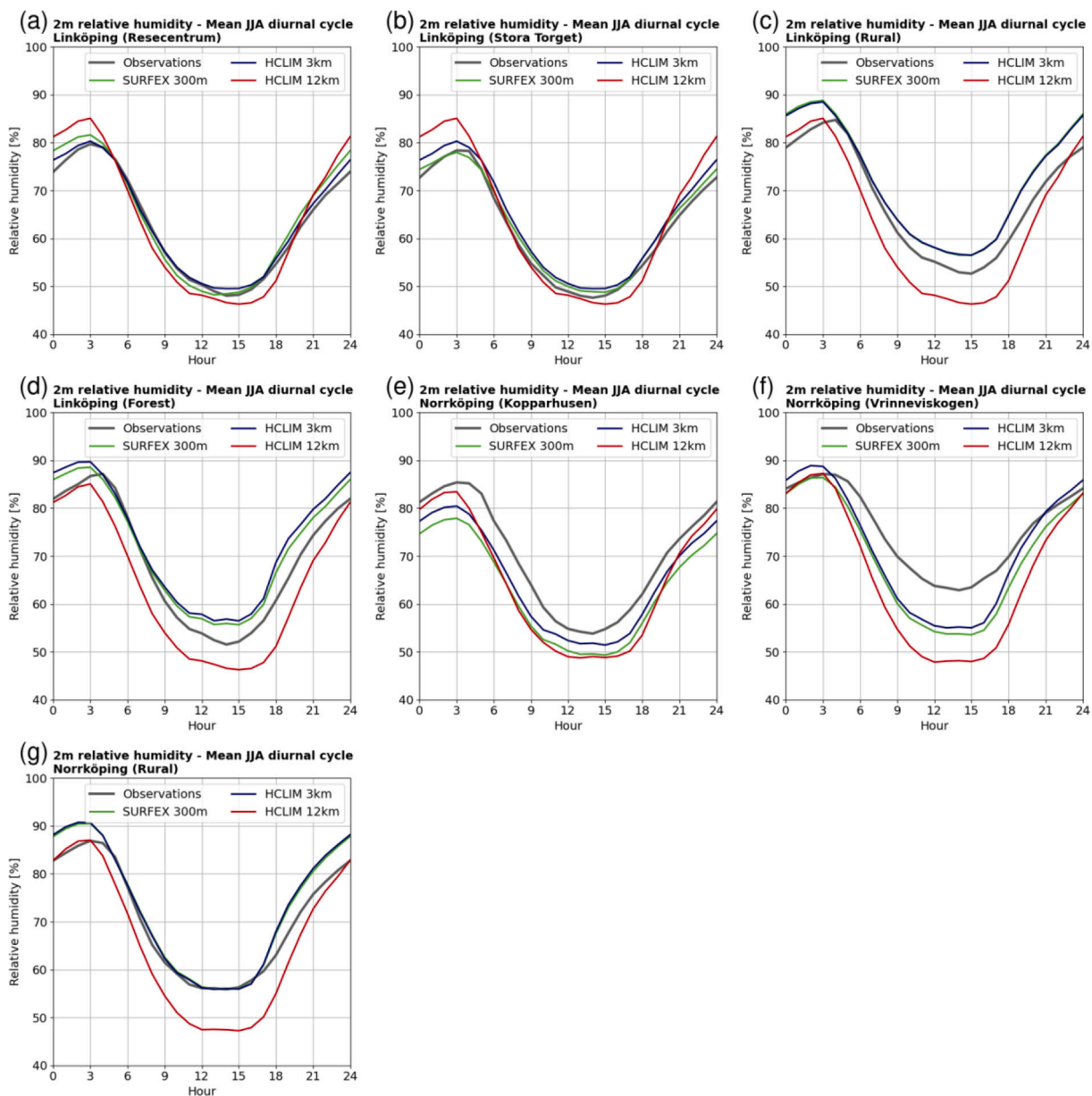


Fig. A4. Same as Fig. 5 but for 2-m relative humidity. The observed 2-m relative humidity for the Östra Promenaden station is unavailable and therefore not included here.

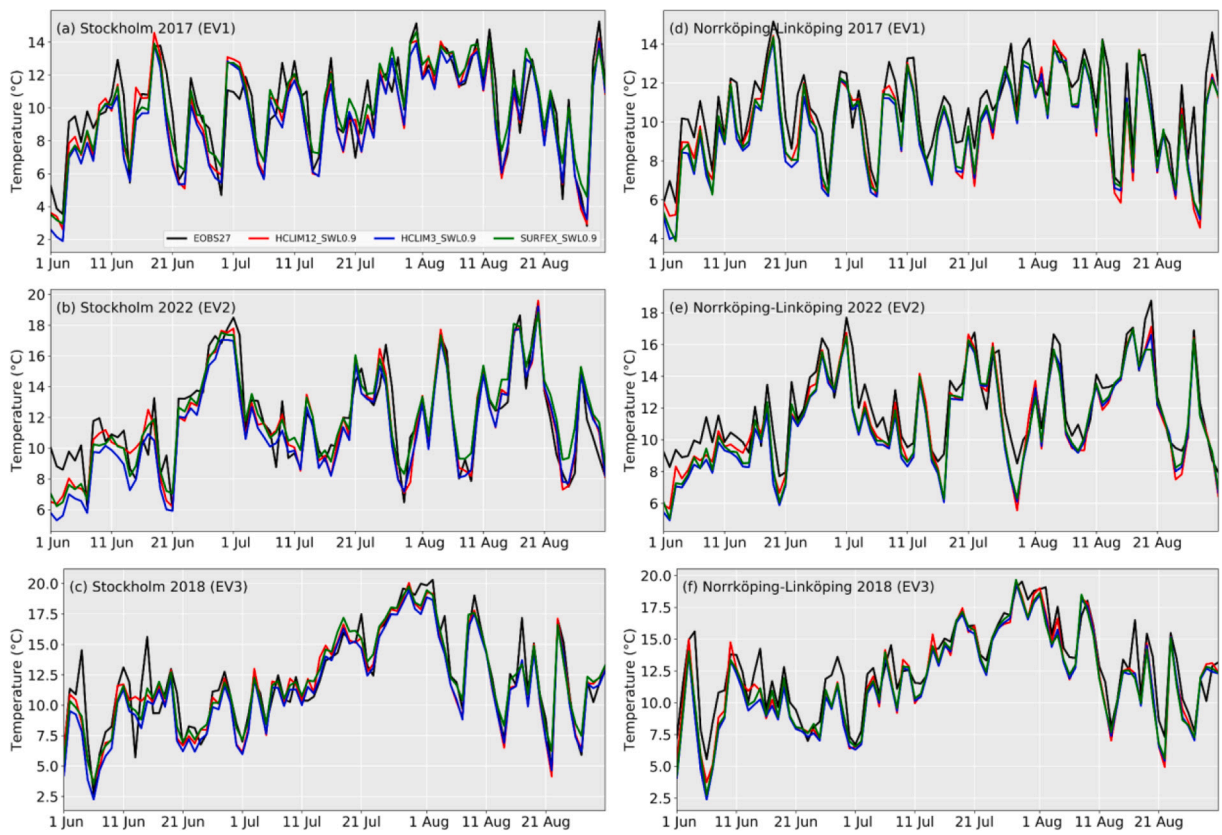


Fig. A5. Same as Fig. 3 but for daily minimum temperature.

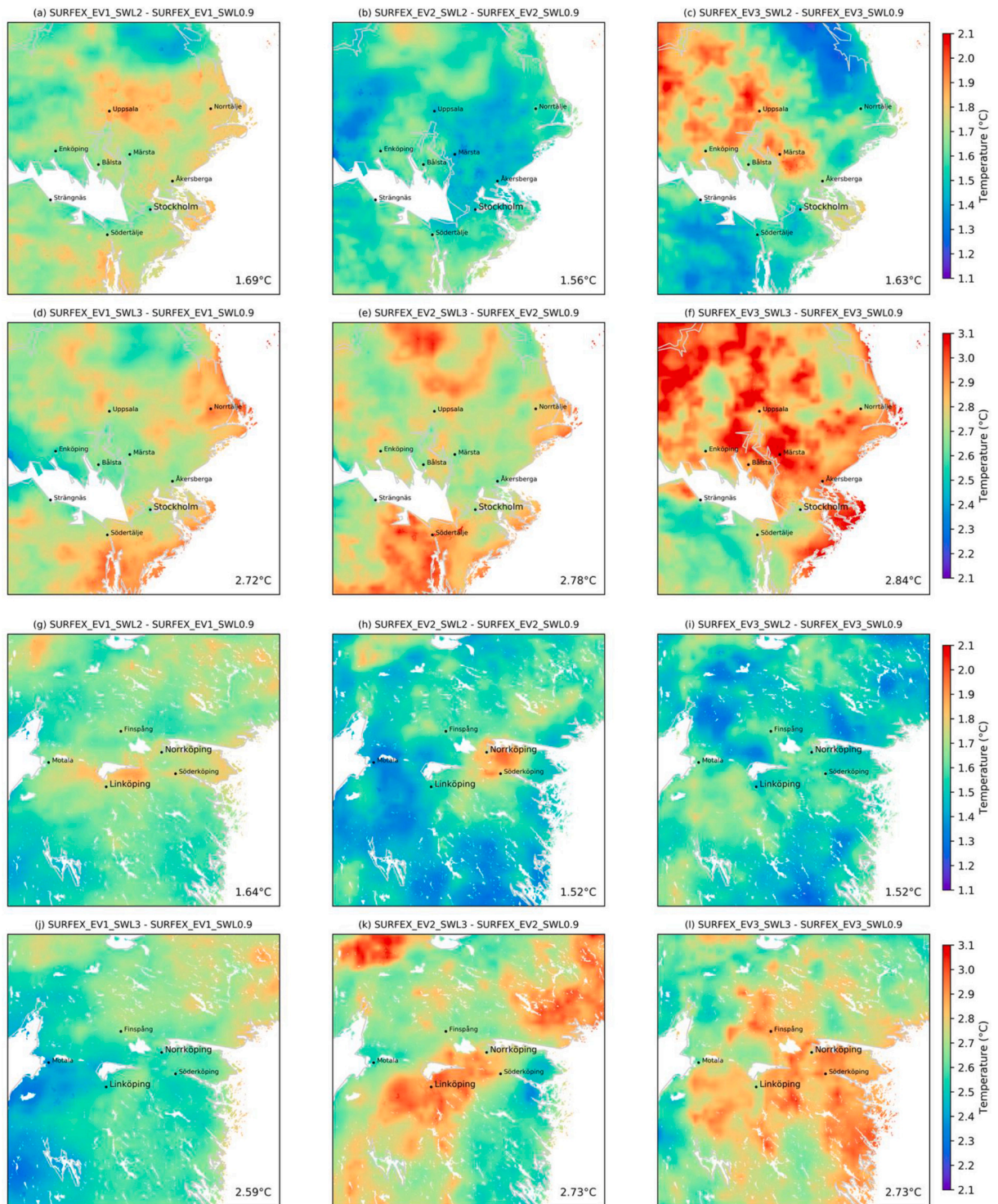


Fig. A6. The change of 2-m air temperature during JJA over Stockholm (a-f) and Norrköping-Linköping (g-l) for EV1 (left), EV2 (middle) and EV3 (right) under SWL2 (a, b, c, g, h, i) and SWL3 (d, e, f, j, k, l) compared to SWL0.9.

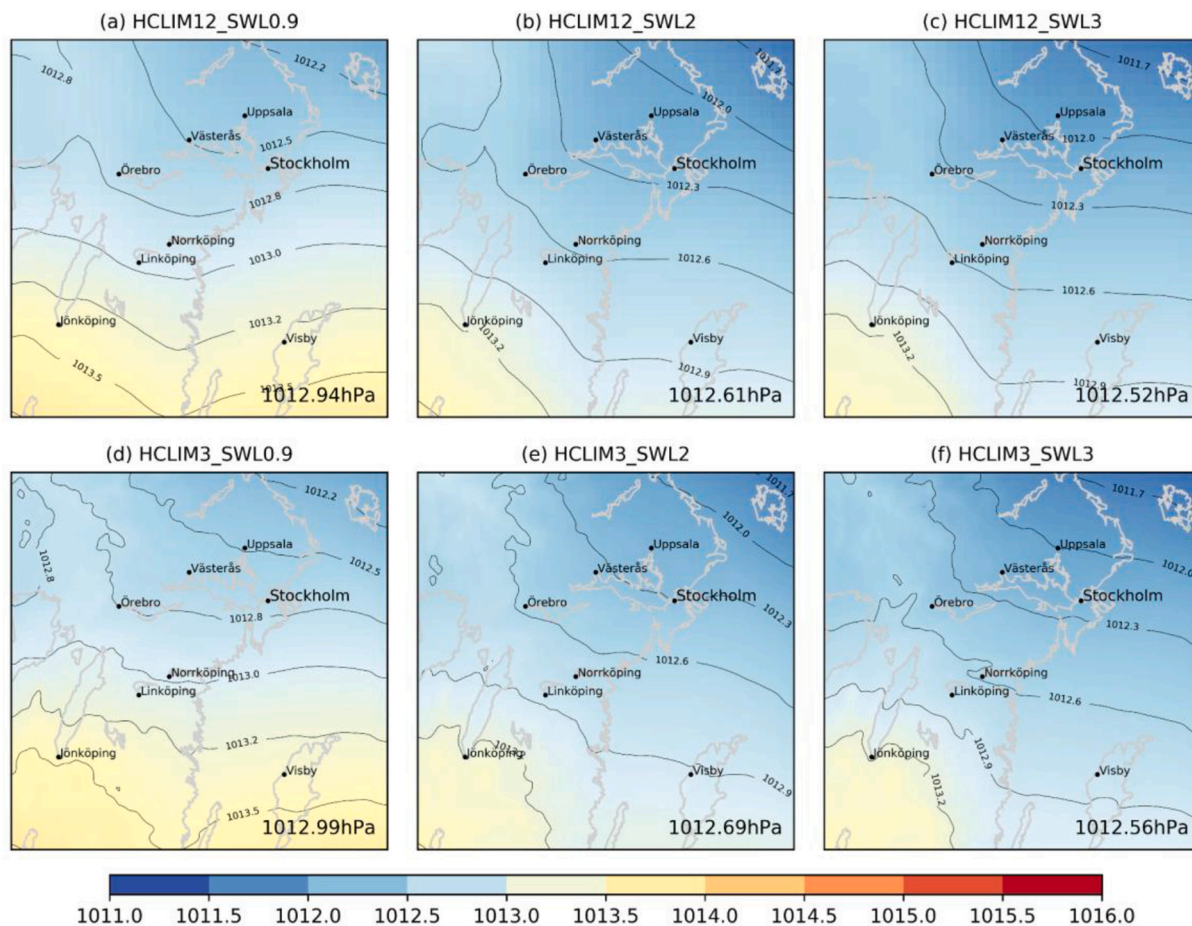


Fig. A7. Spatial distribution of sea level pressure (unit: hPa) averaged over the non-heat wave periods of summer months (June–August) of EV3 (2018) for HCLIM43-AROME 12 km (a-c), and HCLIM43-AROME 3 km (d-f) simulations. Columns represent different warming levels: SWL0.9 (left), SWL2 (middle), and SWL3 (right).

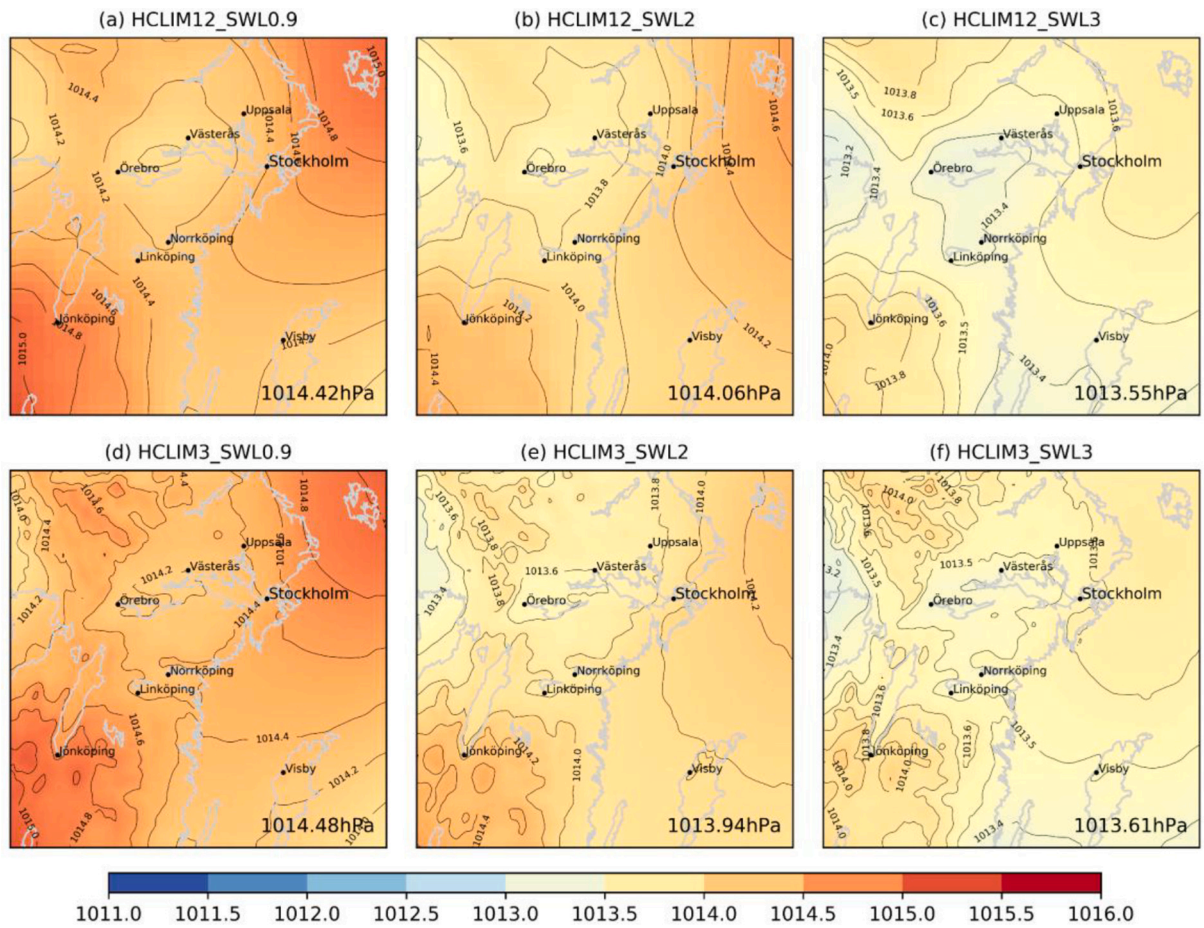


Fig. A8. Same as Fig. A7 but over the heat wave periods (unit: hPa).

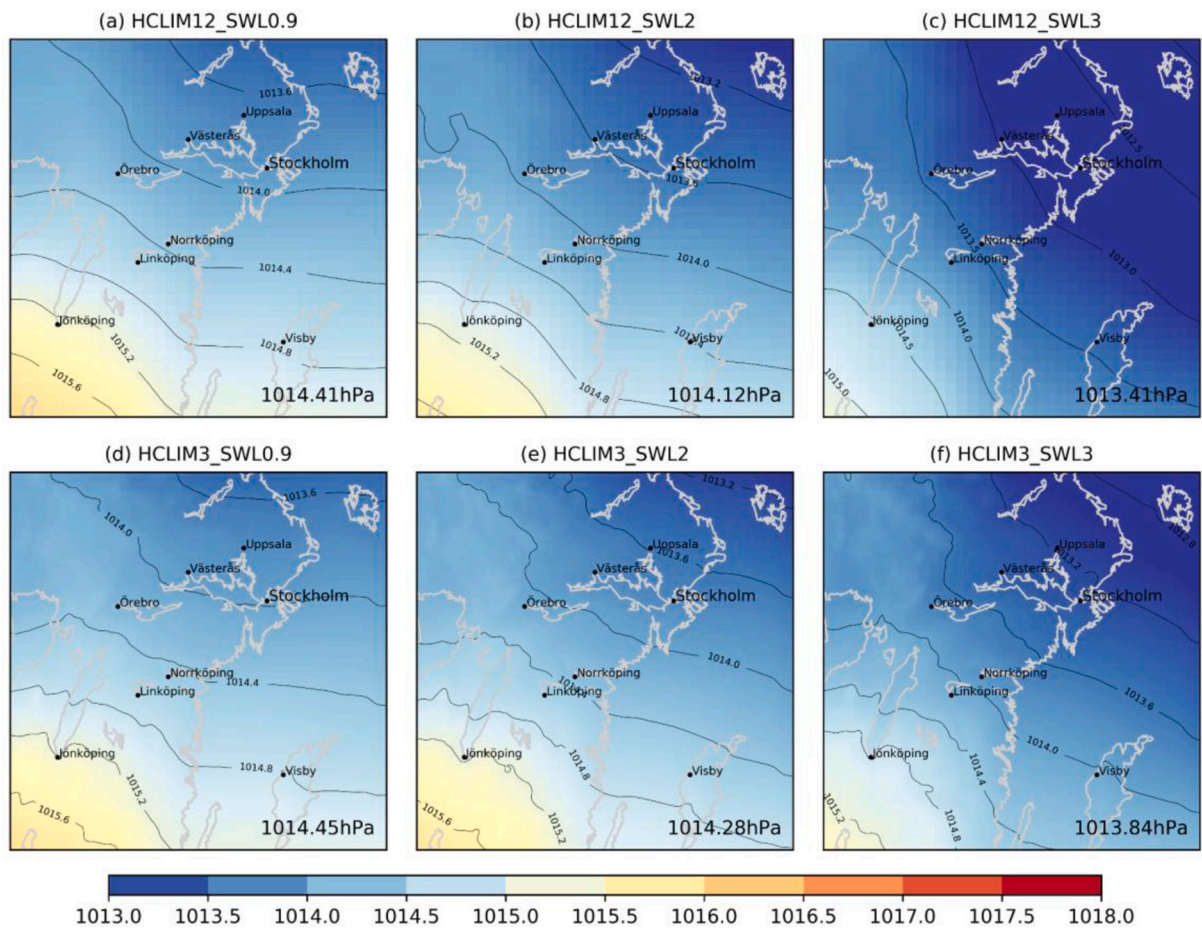


Fig. A9. Same as Fig. A7 but for EV2 (2022, unit: hPa).

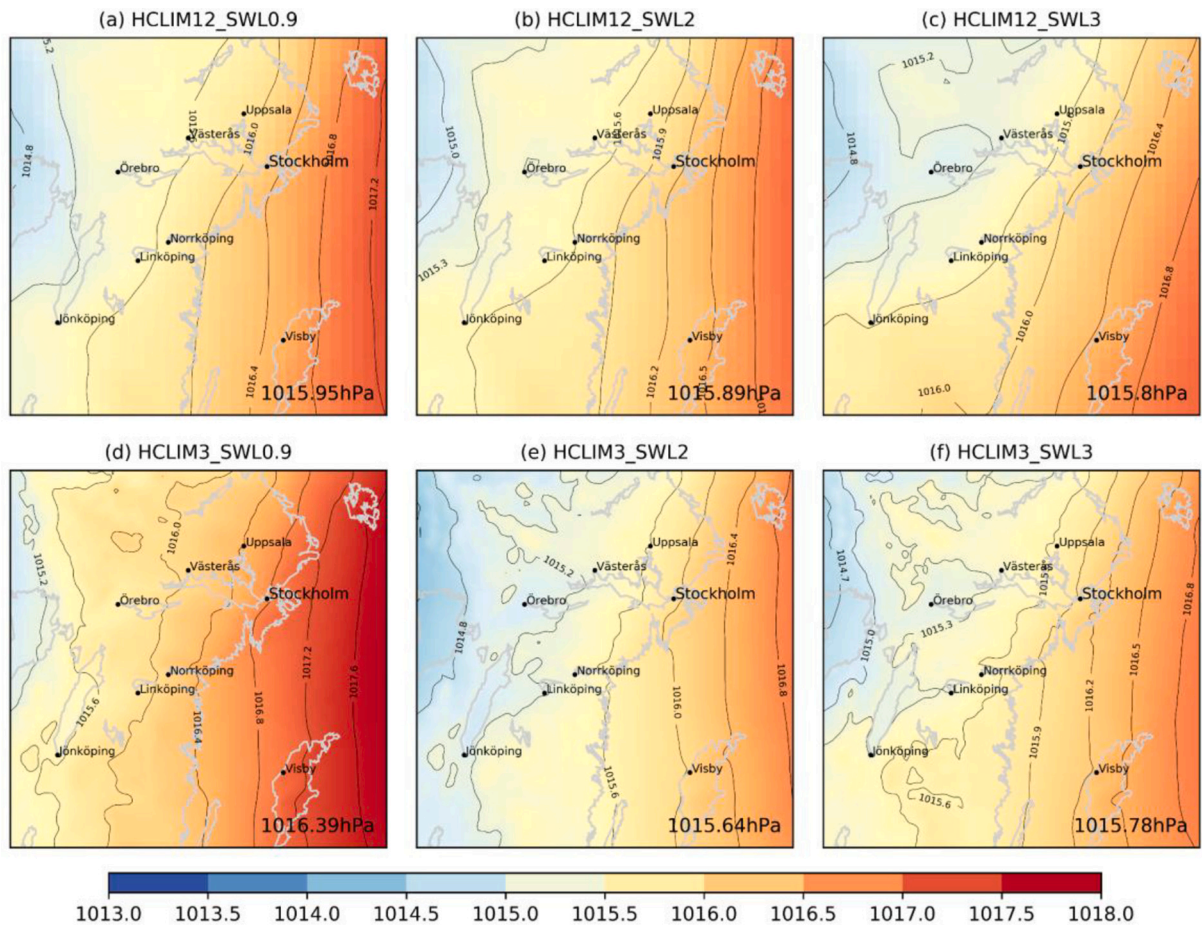


Fig. A10. Same as Fig. A7 but for EV2 (2022) and over heat wave periods (unit: hPa).

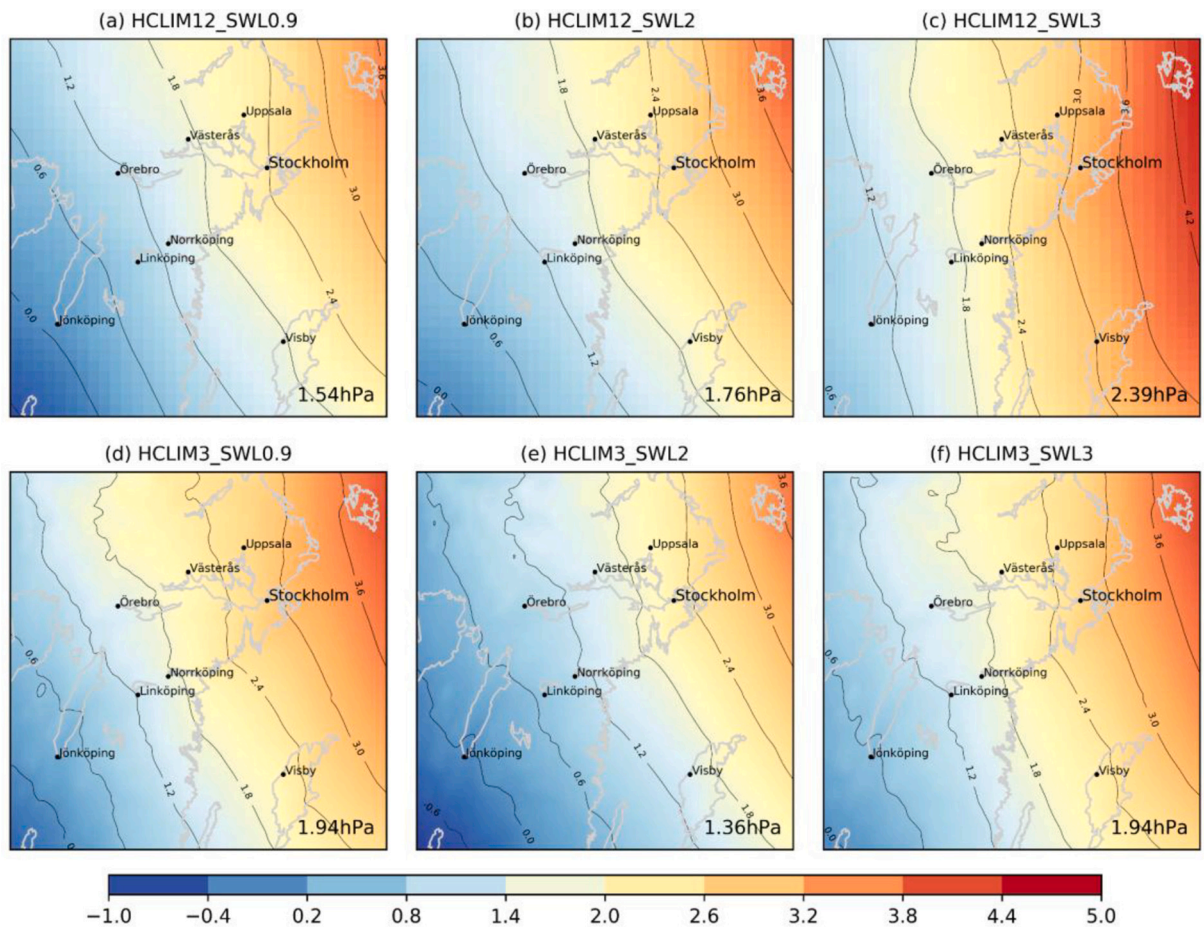


Fig. A11. Same as Fig. A7 but the difference between heat wave and non-heat wave periods for EV2 (2022, unit: hPa).

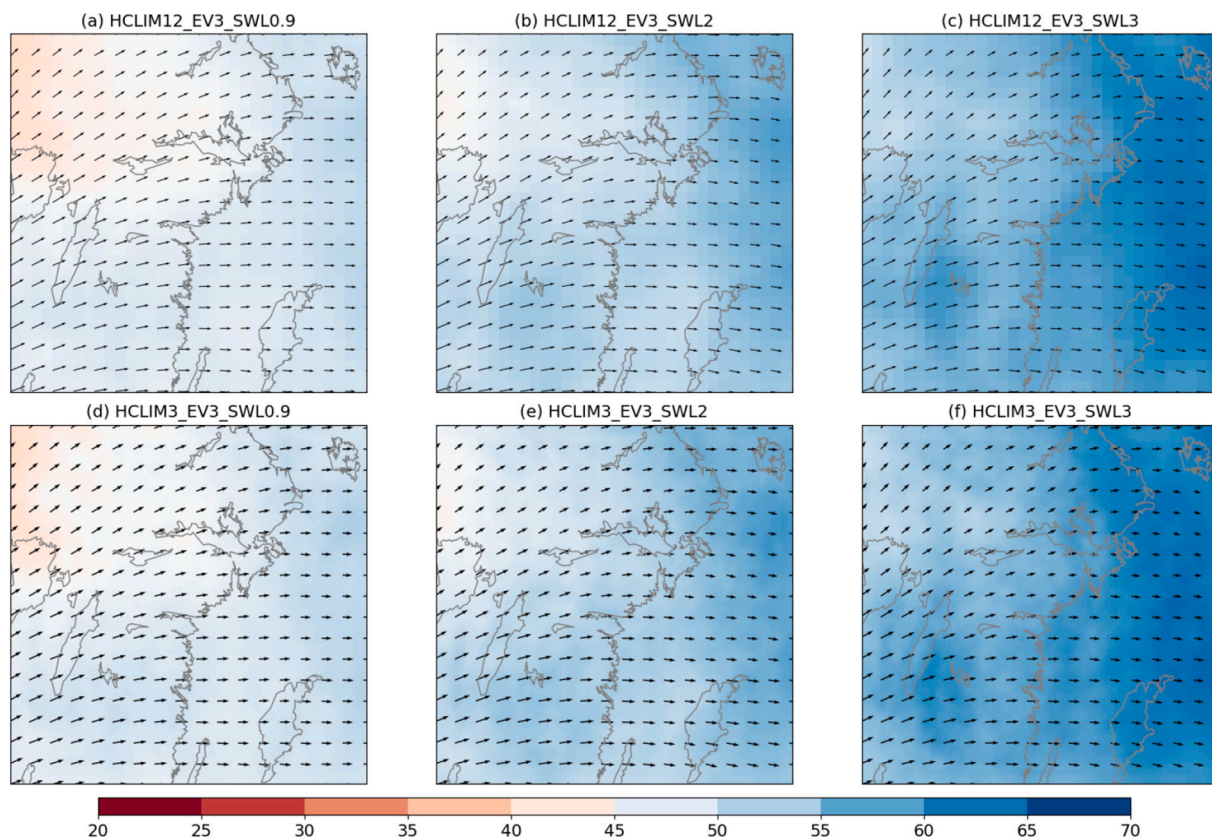


Fig. A12. Spatial distribution of water vapor flux (colour shading, unit: m/s) and wind vectors (arrows) averaged over non-heat wave days during summer months (June–August) of EV3 (2018), as simulated by HCLIM43-AROME at 12 km (a-c) and 3 km (d-f) resolutions. Columns represent different warming levels: SWL0.9 (left), SWL2 (middle), and SWL3 (right).

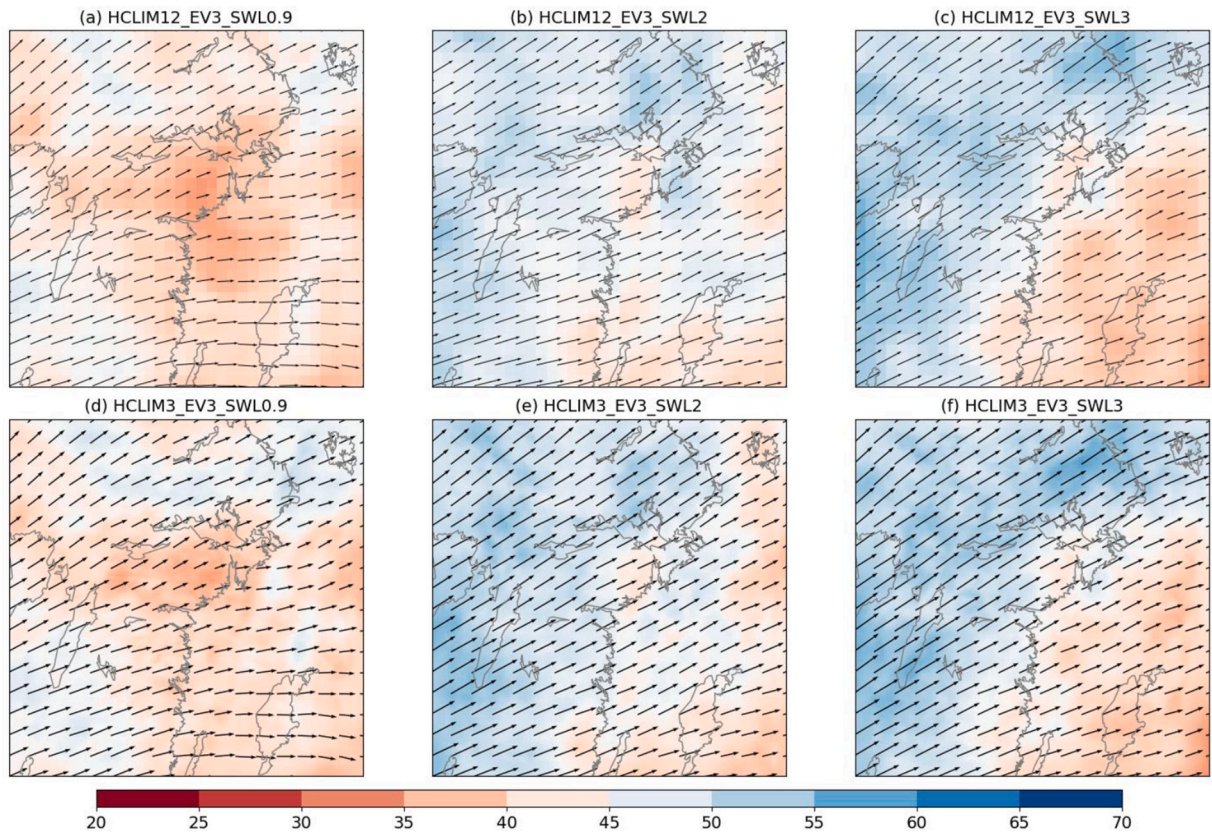


Fig. A13. Same as Fig. A12 but over the heat wave period.

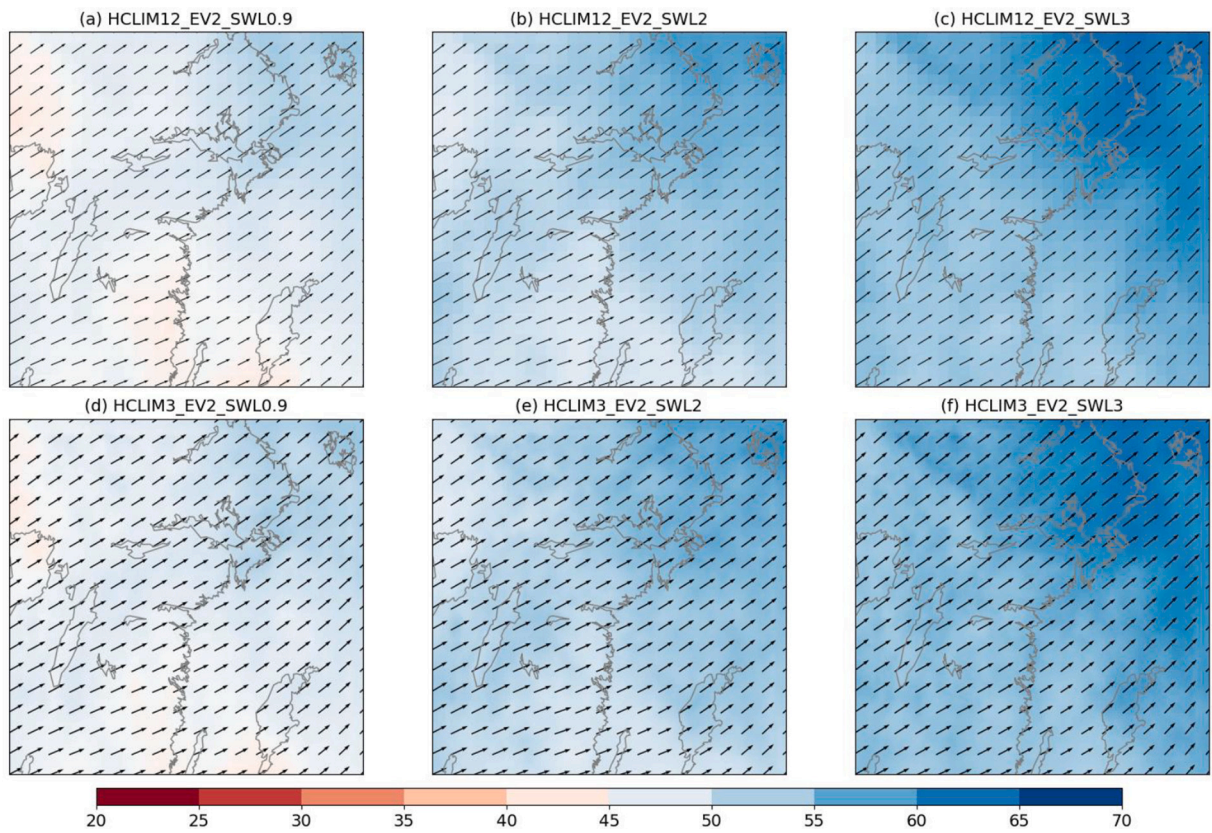


Fig. A14. Same as Fig. A12 but for EV2 (2022).

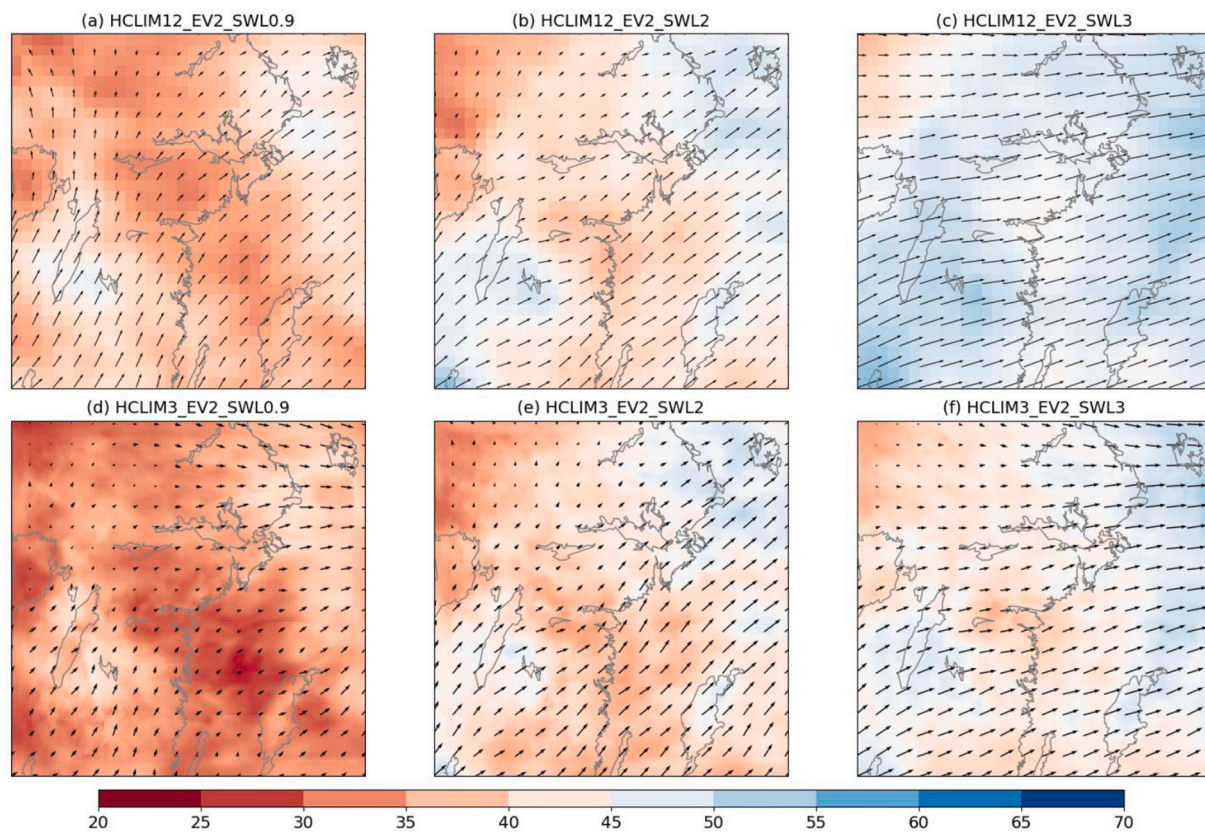


Fig. A15. Same as Fig. A12 but for EV2 (2022) over the heat wave period.

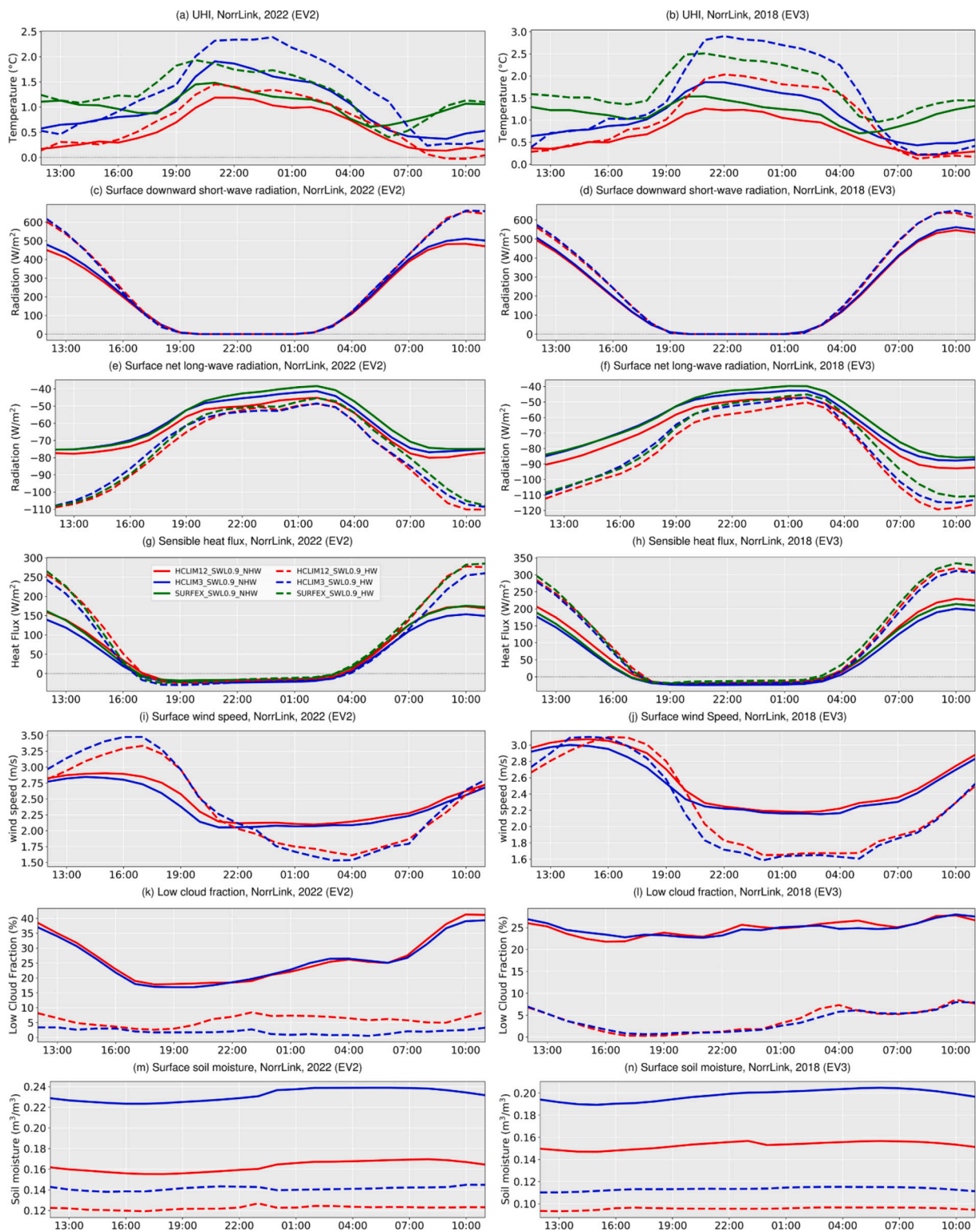


Fig. A16. Same as Fig. 12, but for Norrköping-Linköping.

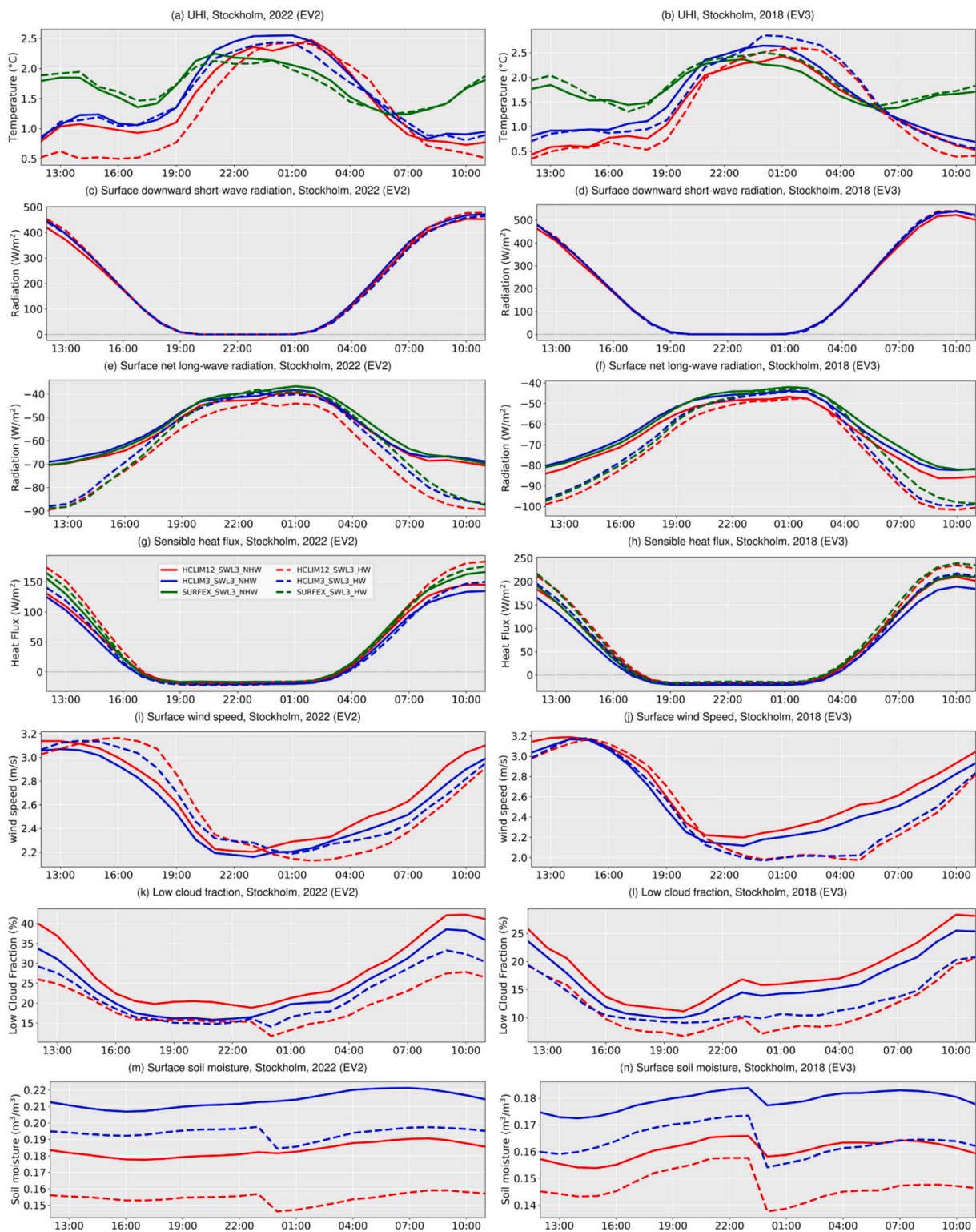


Fig. A17. Same as Fig. 12 but for SWL3.

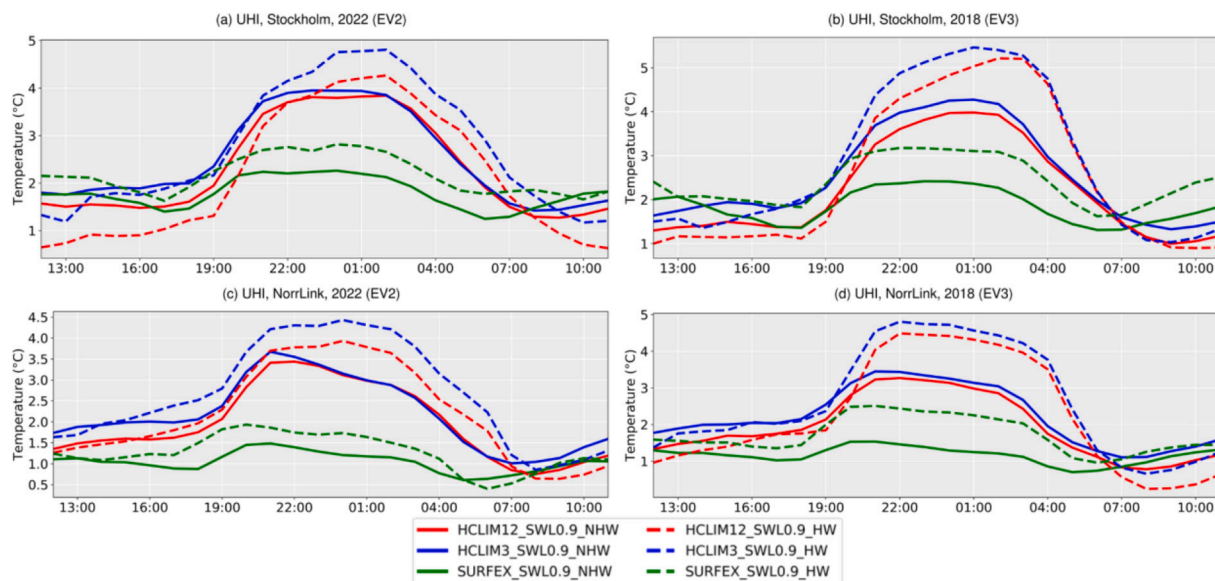


Fig. A18. The diurnal cycle of UHI intensity calculated from T_{2m} over urban tile and averaged over Stockholm (a, b) and Norrköping-Linköping (c, d) domain for EV2 and EV3 under SWL0.9, distinguished between the heat wave (dashed lines) and non-heat wave periods (solid lines).

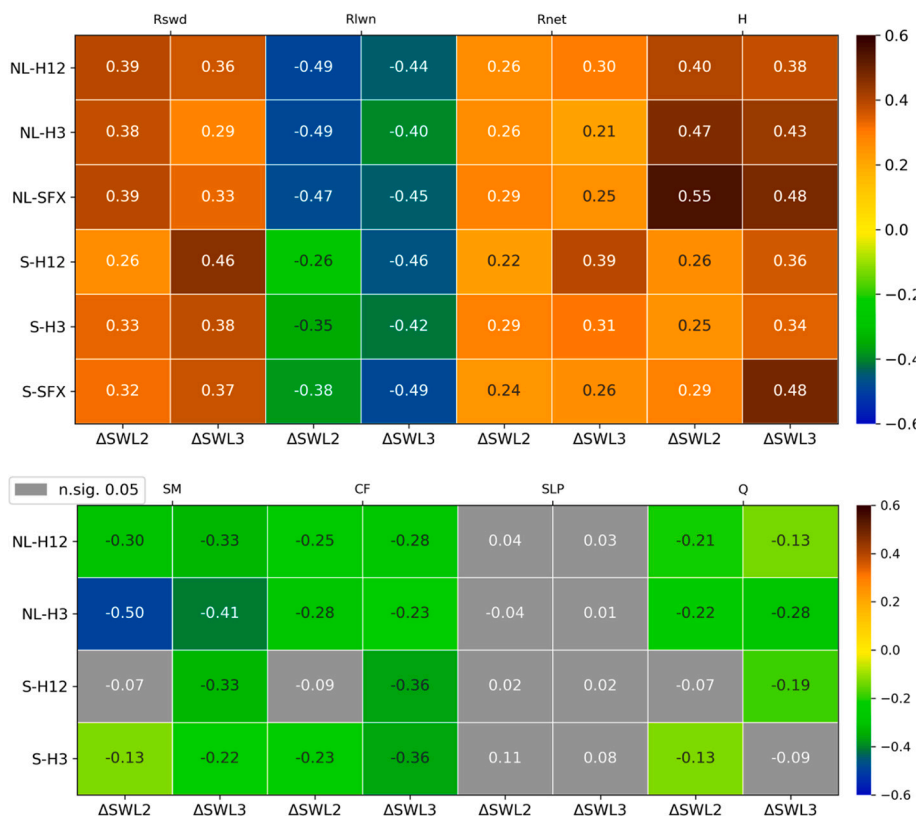


Fig. A19. The heatmap of correlation coefficients between the change of UHI intensity at nighttime (00:00–03:00) and the change of different variables under SWL2 ($\Delta\text{SWL2} = \text{SWL2} - \text{SWL0.9}$) and SWL3 ($\Delta\text{SWL3} = \text{SWL3} - \text{SWL0.9}$): surface downward short-wave radiation (R_{swd}), surface net long-wave radiation (R_{lwn}), surface net radiation (R_{net}), sensible heat flux (H), surface soil moisture for open land (SM), low cloud fraction (CF), sea level pressure (SLP), moisture flux at 850 hPa (Q). On the y-axis, NL, S, H12, H3 and SFX represent Norrköping-Linköping, Stockholm, HCLIM43-AROME at 12 km, HCLIM43-AROME at 3 km and SURFEX 300 m, respectively.

Data availability

Data will be made available on request.

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