



Assessing the impacts of physiography refinement on Stockholm summer urban temperature simulated with an offline land surface model

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ABSTRACT

Urban climate information at high spatial resolution (tens or hundreds meter scale) is needed for local climate adaptation. Due to the high demand for computational resources by convection-permitting models (CPMs) that can resolve urban areas and the general lack of accurate urban physiography information, the downscaling of climate data to sub-km scale is challenging. This work explores the feasibility of simulating urban air temperatures using a much less computationally expensive offline land surface model (LSM) with refined physiography. The method is based on the SURFEX LSM downscaling to 300 m of a set of CPM simulations with an original grid spacing of 3 km. Results show that the influence of different physiography in the CPM atmospheric forcing on the SURFEX simulations decreases with the increase of forcing height, and it becomes statistically non-significant at a forcing height of 50 m or above. On the other hand, the impacts of physiography change on 2-m temperature (T2m) simulated by the offline LSM are highly correlated when using different physiography in the CPM simulations, regardless of the forcing height. The refined physiography dataset was produced using open-access products, which enables the proposed method to be used in other regions.

1. Introduction

The urban share of the world population has reached 55% in 2018 and is projected to grow to 68% by 2050 (United Nations., 2018). The global urban land area expanded by a rate of approximately 5% annually between 1970 and 2010 (Güneralp et al., 2020), and it is predicted to increase by a factor of 1.8–5.9 over the 21st century depending on different socioeconomic scenarios (Gao and O'Neill, 2020). Urbanisation plays an important role in affecting local climate characteristics (e.g., Li et al., 2016). Heat waves in urban areas are particularly important because they can amplify urban heat island (UHI) effects, which can further increase the risk of morbidity and mortality (Li and Bou-Zeid, 2013). Furthermore, urban areas will be affected by more frequent heat waves under global warming (IPCC, 2021). To take into account the meteorological effects in urban planning and climate change adaptation, climate information at high spatial resolution is needed (Bai et al., 2018; Masson et al., 2020).

Over the last two decades, urban parameterizations have been implemented in the land surface component of climate models to take into account the interactions between the complex surface physiography and the atmosphere (e.g., Hamdi et al., 2020). To

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produce detailed and accurate climate data over urban areas, high resolution dynamical downscaling with meteorological or regional climate models (RCMs) is applied (e.g., Daniel et al., 2019; Gidhagen et al., 2020). The horizontal resolution of RCMs is usually around 10–50 km (e.g., Jacob et al., 2020). Recently, RCMs have shifted to more advanced convection-permitting models (CPMs) which show great benefits over regions of strong spatial heterogeneities such as urban areas (Argüeso et al., 2016; Amorim et al., 2020; Mussetti et al., 2020). CPMs can run at spatial resolutions as high as kilometer or even sub-kilometer scale.

The km scale simulations by CPMs deepen the understanding of climate processes and provide detailed climate information at regional scale. However, for local climate change adaptation, even higher resolution (hundreds meters scale) is required, but the further downscaling with CPMs is challenging because of the high demand of computing resources (Prein et al., 2015; Gidhagen et al., 2020) and the validity of parameterizations at this resolution. An alternative solution is to run land surface models (LSMs) offline with prescribed atmospheric forcing, i.e. not coupled to the atmospheric model. Zsebeházi and Szépszó (2020) and Zsebeházi and Mahó (2021) applied the LSM SURFEX (Surface Externalisée, Masson et al., 2013) driven by the ALADIN-Climate RCM (Colin et al., 2010) to simulate the UHI evolution over Budapest. The authors concluded that although SURFEX in offline mode overestimated the surface UHI compared to MODIS, the model captured the main features of the urban warming and revealed promising long term (1971–2000) results for air temperature at 2-m above the surface (T2m) when evaluated against station measurements (Zsebeházi and Mahó, 2021). Besides, this solution requires less computing resources and therefore can run at very high spatial resolution (e.g., hundred meters) over a long period of time (decadal or longer). Hamdi et al. (2014) studied the sensitivity of offline SURFEX at 1 km resolution with town scheme TEB (Masson, 2000) to different atmospheric forcings obtained from ALARO (Gerard et al., 2009) model simulations at 4 km. The TEB scheme was activated in one ALARO simulation but it was deactivated in the other. The authors found that the different atmospheric forcings from ALARO can affect the UHI simulations when using offline SURFEX over Brussels.

With the increase of model horizontal resolution, more detailed surface information is required for the LSM downscaling to have any added value (e.g. Gidhagen et al., 2020). A potential issue in this process is that the physiography used in the forcing CPM might be different from that in the offline LSM. An assumption to be investigated is that a consistency in physiography between the forcing CPM and the driven offline LSM simulation is needed, implying that the CPMs should use local physiography data. However, physiography databases do not always offer the required spatial detail when running with grid cell spacing below 2–3 km (e.g. Amorim et al., 2020). Similarly, studying the effects of various levels of changing physiography in the present or future climate (e.g. due to urbanisation plans) would require a number of multi-year CPM simulations, which are prohibitively computationally expensive. Therefore, it is necessary to study the feasibility of downscaling with offline LSMs using refined local physiography with the goal of producing more accurate urban climate data within viable CPU time. Specifically, this study aims to answer the following research question: Can a high resolution offline LSM using refined urban physiography be forced by CPM simulations produced with a different physiography? By different we mean the generic physiography dataset used by default in the CPM. This question is further split into two sub-questions:

- How sensitive is the LSM T2m to different CPM forcing?
- How sensitive are the effects of LSM physiography changes on T2m to different CPM forcing?

The first question addresses the applicability of LSM to reproducing T2m, if it has a different physiography compared to the forcing dataset. The second question addresses if the effects of physiography changes within the LSM (e.g. urbanisation) on T2m can be robustly reproduced even with different forcing datasets.

To answer these questions, we analyse the impacts of atmospheric forcing and physiography changes on T2m by comparing offline LSM simulations performed by different combinations of atmospheric forcing and physiography. This study focuses on T2m because it is the most frequently used variable in heat stress assessment studies. We chose July 2018 over Stockholm, where one of the most important heat waves in this region occurred (Wilcke et al., 2020).

2. Method

2.1. Models

For the purpose of studying the sensitivity of T2m to land surface physiography refinement, the HCLIM RCM (Belušić et al., 2020) and SURFEX LSM (Masson et al., 2013) are used. HCLIM is an RCM containing different atmospheric physical packages and here we use the HCLIM version/cycle 38 with the AROME atmospheric physical package (HCLIM38-AROME; Belušić et al., 2020; Lind et al., 2020). HCLIM38-AROME runs at convection-permitting scales with nonhydrostatic dynamics; in this study, at 3 km grid spacing and 60 s time step. For simplicity, the term HCLIM is used hereinafter to refer to HCLIM38-AROME. SURFEX contains various physical models that enable the simulation of surface processes in HCLIM. The subgrid surface heterogeneity is represented by four tiles which encompass continental natural surfaces, sea, inland water and urban areas. Urban surfaces are simulated by the TEB (Town Energy Balance; Masson, 2000) scheme that is based on the Urban Canyon approach (Nunez and Oke, 1977), with the option to simulate urban green areas by the GARDEN module (Lemonsu et al., 2012) and the GREENROOF module (De Munck et al., 2013). The representation of trees in town is available in SURFEX v8.0 (Redon et al., 2017, 2020). Natural surfaces are parameterized using ISBA (Noilhan and Planton, 1989). The inland water is simulated by the lake model FLake (Mironov et al., 2010). Sea surface temperature is taken from an external data source.

In HCLIM, SURFEX is coupled to the atmosphere, whereas in its offline mode the feedback from land to the atmosphere is not considered. The SURFEX offline model is forced by the following atmospheric variables: rainfall rate, snowfall rate, surface pressure, surface downward short-wave radiation (direct and scattered components separately), surface downward long-wave radiations, and at

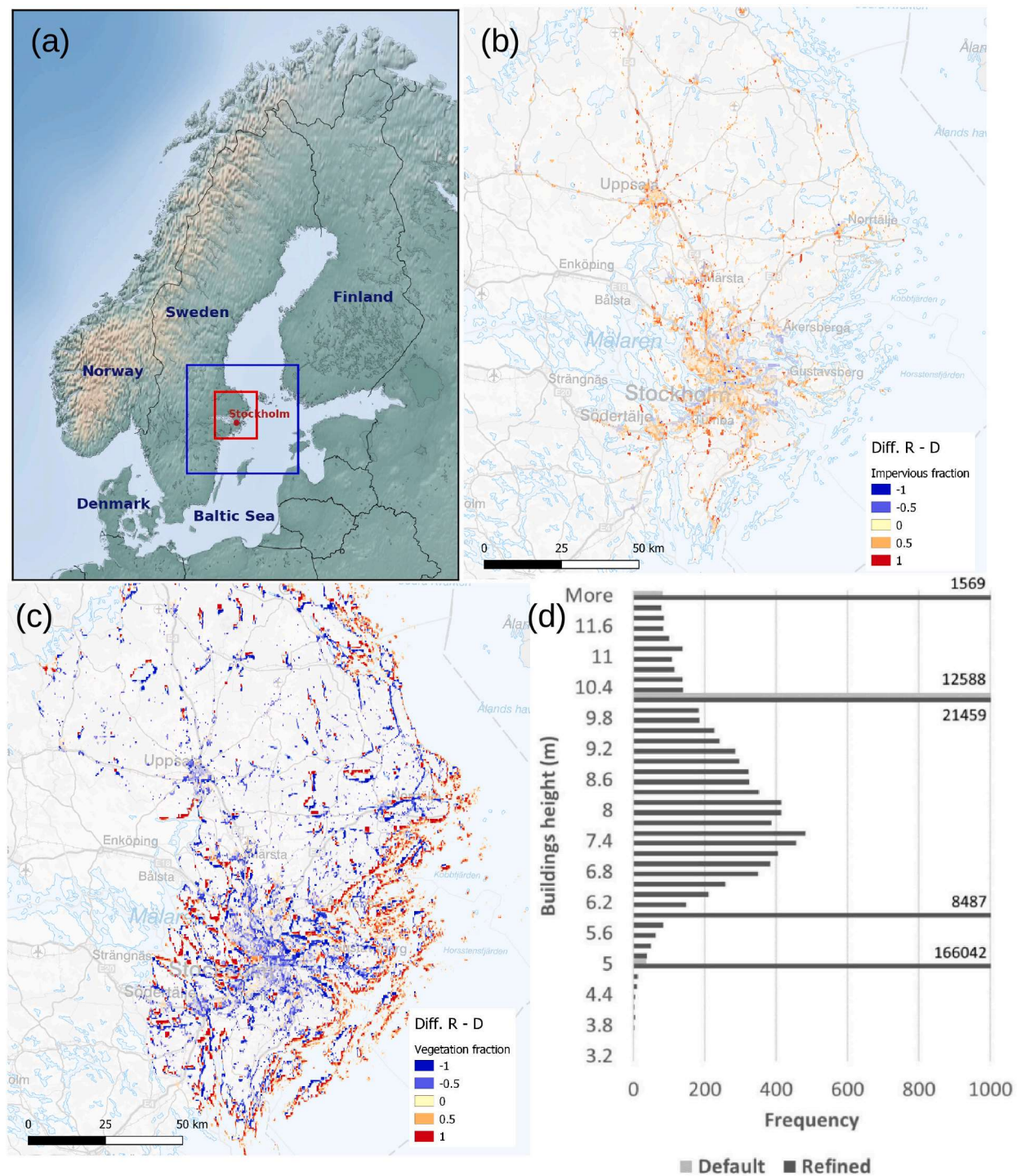


Fig. 1. (a) Simulation domain for HCLIM (blue) and SURFEX offline (red), nested in the NorCP 3-km domain (see Section 2.3). Difference in (b) impervious and (c) vegetative surfaces (including both NATURE and GARDEN surfaces) between the refined and the default physiography databases shown over an area coinciding with SURFEX domain and with the original spatial resolution of 0.0042° . (d) Histogram of building height at each grid cell for refined (black) and default (grey) physiography sampled over the same area as in (b, c). The y-axis is cut-off for the sake of readability, with the values close to these bars indicating the respective peak frequencies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a chosen height above buildings also air temperature, specific humidity, wind speed and wind direction. One advantage of running SURFEX in offline mode is that it is less computationally expensive than in the coupled HCLIM setup, thus being able to run at horizontal resolution as high as 100 m or for long time periods (multiple decades). In this study, SURFEX offline is applied at 300 m resolution and 60 s time step. The hourly outputs of HCLIM are interpolated to the resolution of SURFEX offline model by bilinear interpolation method, and the interpolated data is used to force SURFEX offline.

The offline simulations are performed using the same version of SURFEX as in HCLIM (see Belušić et al., 2020). SURFEX version 7.2 (implemented by default in HCLIM38) was upgraded to version 7.3 for all modules except ISBA, for which version 8.1 was used. The study domain is Stockholm city and the surrounding region (Fig. 1a). The computational domain for the SURFEX offline simulation is smaller than the HCLIM simulation to avoid potential spatial spin-up inaccuracies at the lateral boundaries of the HCLIM simulation (e.g. Matte et al., 2017), even though the current simulation setup is such that the spatial spin-up effects are minimised (see section 2.3).

2.2. Physiography data

The main urban land cover parameters used by TEB include geometric parameters (fractional area occupied by buildings, urban vegetation, and roads; building height; aspect ratio and dynamic roughness length for building and canyon; etc.), radiative parameters (albedos and emissivities for roof, road, and wall; etc.) and thermal parameters (thickness, thermal conductivity and heat capacity of each model layer for roof, road or wall; etc.) (Le Moigne, 2012). SURFEX differentiates natural cover from impervious surfaces and it incorporates vegetation inside the urban canyon via the TEB-GARDEN module (Lemonsu et al., 2012).

Two physiography datasets are used in this study. The default physiography is ECOCLIMAP version 2.2, which is a dataset of ecosystems and land surface parameters at 1 km resolution (Faroux et al., 2013). The refined physiography has a spatial resolution of 0.0042° (approximately $240 \times 460 \text{ m}^2$ over Stockholm) and provides detailed urban physiography description combining ECOCLIMAP 2.2, Copernicus land services and national databases, as described in Amorim et al. (2020). The new physiography files describe (i) the spatial fractions of each land-use type; (ii) the height of buildings and their wall to horizontal area ratio; and (iii) the seasonal variation of Leaf Area Index (LAI). With the goal of allowing this method to be used in other cities, this dataset was produced using only open-access products (for details see Table 1 in Amorim et al., 2020), which ultimately increases the scope and applicability of the conclusions from this article.

Figs. 1b–1c map the difference in the fractions of impervious and vegetated surfaces between the refined and the default physiography maps (note that these represent the high resolution databases, which were subsequently interpolated by SURFEX, both online and offline). Considering the spatial domain shown in this figure, the total area covered by buildings/roads, vegetation and water is changed in the refined database by, respectively, 107.6%, 0.0% and -2.6% , corresponding to 348.02 km^2 , -2.94 km^2 and -345.08 km^2 . This is a result of a better mapping of the fraction of built-up infrastructure across the city, but also a more realistic description of inland waters (in particular, the 1000 km^2 lake Mälaren) and of the Baltic Sea coastline. Although the total green area remains almost unchanged, the refinement improved the spatial distribution of vegetation (e.g., less green in the city center compensated by greener outskirts and lake/sea shorelines). Moreover, this method implemented a conversion of NATURE tiles into GARDEN (a fraction of the TOWN tile) over the city, which allows an enhanced interaction between the impervious surfaces and the vegetation within the street-canyon (for more details about the tiling process in SURFEX see Masson et al., 2013). The new surface dataset offers also a more accurate description of building heights based on Lidar measurements at 12.5 m resolution. This higher resolution physiography counts over 205,000 grid cells with building height information, with a mean height of 5.77 m (St. dev. 1.91 m), against 10.07 m (St. dev. 1.16 m) and only 12,700 cells in ECOCLIMAP 2.2. Moreover, and as depicted in the histogram of Fig. 1d, it offers a much more refined distribution of heights than the default, where 99% of the urbanised grid cells had a predefined height of 10 m.

Table 1

The set of simulations performed with HCLIM and SURFEX.

Experiment	Model	SURFEX/HCLIM physiography	Resolution	Forcing (level and/or height)
HCLIM _D	HCLIM	-/D	3 km	–
HCLIM _R	HCLIM	-/R	3 km	–
SURFEX _R HCLIM _D L65	SURFEX	R/D	300 m	HCLIM _D (L65)
SURFEX _R HCLIM _R L65	SURFEX	R/R	300 m	HCLIM _R (L65)
SURFEX _R HCLIM _D L62	SURFEX	R/D	300 m	HCLIM _D (L62)
SURFEX _R HCLIM _R L62	SURFEX	R/R	300 m	HCLIM _R (L62)
SURFEX _R HCLIM _D H50m	SURFEX	R/D	300 m	HCLIM _D (50 m)
SURFEX _R HCLIM _R H50m	SURFEX	R/R	300 m	HCLIM _R (50 m)
SURFEX _D HCLIM _D L65	SURFEX	D/D	300 m	HCLIM _D (L65)
SURFEX _D HCLIM _R L65	SURFEX	D/R	300 m	HCLIM _R (L65)
SURFEX _D HCLIM _D L62	SURFEX	D/D	300 m	HCLIM _D (L62)
SURFEX _D HCLIM _R L62	SURFEX	D/R	300 m	HCLIM _R (L62)
SURFEX _D HCLIM _D H50m	SURFEX	D/D	300 m	HCLIM _D (50 m)
SURFEX _D HCLIM _R H50m	SURFEX	D/R	300 m	HCLIM _R (50 m)

'R' means refined physiography obtained from local physiography data; 'D' means the default physiography from ECOCLIMAP 2.2. The approximate heights of model levels are: L62 ($\sim 90 \text{ m}$), L65 ($\sim 12.5 \text{ m}$).

2.3. Model experiments

All simulations were performed from 1 to 31 July 2018 over Stockholm. In this period, the large-scale circulation was dominated by high-pressure systems over Scandinavia that resulted in extremely warm and dry conditions (Sinclair et al., 2019). Over Stockholm, the average T2m during the period from May to August 2018 reached 17.8°C, which is 3.0°C higher than the mean for 1998–2017 and 4.0°C higher than the mean for 1756–1900 (Wilcke et al., 2020).

The physiography sensitivity experiments were designed as follows (see Table 1):

- (1) HCLIM simulations with two different physiography fields. Two HCLIM simulations were performed at 3 km resolution using the default (HCLIM_D) and the refined physiography (HCLIM_R). In HCLIM_R simulation, the refined physiography data were interpolated to 3 km resolution by spline interpolation method. These two simulation outputs are used to force SURFEX offline simulations in different combinations. The boundary data for these HCLIM simulations are obtained from the Nordic Convection Permitting Climate Projections (NorCP) project that produced two-decade long climate simulations at 3 km grid spacing over the Fenno-Scandinavia region (Fig. 1a; Lind et al., 2020, 2022) using ECOCLIMAP 2.2. In NorCP, ERA-Interim was used as the lateral boundary data for an intermediate RCM simulation at 12 km, which was further downscaled to 3 km. The outputs from the latter were used as lateral boundary data for HCLIM_D and HCLIM_R in this study. This implies that the same model and resolution were used for the boundary data, minimising potential lateral boundary spin-up effects.
- (2) SURFEX offline simulations at 300 m grid spacing with the refined physiography (SURFEX_R) forced by HCLIM_D and HCLIM_R outputs (SURFEX_R_HCLIM_D and SURFEX_R_HCLIM_R). These two SURFEX_R simulations are compared to understand the impacts on SURFEX simulations resulting from the mismatch in physiography between the default CPM atmospheric forcing and the refined offline LSM. Sensitivity tests are performed by using the atmospheric forcing at different heights above buildings for the following variables: air temperature, specific humidity, meridional and zonal wind speed. SURFEX_R_HCLIM_D_L₆₅ and SURFEX_R_HCLIM_R_L₆₅ are forced by atmospheric forcing at the lowest model level (L₆₅) which is at about 12.5 m. Similarly, atmospheric forcing was used at the height of 50 m (SURFEX_R_HCLIM_D_H_{50m}, SURFEX_R_HCLIM_R_H_{50m}) and at the model level 62 (about 90 m, SURFEX_R_HCLIM_D_L₆₂, SURFEX_R_HCLIM_R_L₆₂). Note that HCLIM uses a hybrid sigma pressure coordinate system, with the atmospheric model levels following the orography close to the surface and becoming isobaric at higher altitude. The output at 50 m was interpolated to that height during post-processing. The reason for choosing forcing height at 50 m is to test the applicability of forcing at both heights and model levels for SURFEX offline simulations.
- (3) SURFEX offline simulations with the default physiography (SURFEX_D) forced by both HCLIM_D and HCLIM_R. The aim of these simulations is to study the impacts of changes in physiography on T2m using offline SURFEX. This is done firstly by comparing the simulations with SURFEX_D and SURFEX_R forced by HCLIM_D (SURFEX_D_HCLIM_D vs SURFEX_R_HCLIM_D). Secondly, in order to understand the sensitivity of the impacts of physiography change to different atmospheric forcing data, we compare the SURFEX physiography change results forced by both HCLIM_D and HCLIM_R (the changes between SURFEX_D_HCLIM_D and SURFEX_R_HCLIM_D are compared to the changes between SURFEX_D_HCLIM_R and SURFEX_R_HCLIM_R).

The atmospheric forcing and initial conditions for the SURFEX offline simulations are obtained from the corresponding HCLIM simulations. The model outputs are at hourly scale.

2.4. Statistical analysis

For the comparison we focus on T2m simulated by SURFEX and air temperature (at L₆₅, L₆₂, H_{50m}) by HCLIM. The time periods 15:00–18:00 and 00:00–03:00 (local time) are selected to represent daytime and nighttime based on summer daytime length at the 59°N latitude of Stockholm.

The root-mean-square deviation (RMSD) is used to measure the difference in T2m from different SURFEX offline simulations. We also apply the Student's *t*-test (*P* value: 0.05) to examine the significance of the difference between experiments. The Pearson correlation coefficient is applied in two aspects: (1) the correlation between the RMSD (or the *P*-value of *t*-test) for different SURFEX simulations and physiography changes (section 3.2); (2) the correlation between the changes in T2m fields in relation to the corresponding changes in the spatial variation of land cover (section 3.3). The coefficient of determination (the square of coefficient of correlation) is used to calculate the relationship between the changes in physiography and the corresponding difference in air temperature (section 3.3).

3. Results and discussion

In the following sections different pairs of model experiments are compared, as schematically shown in Fig. 2.

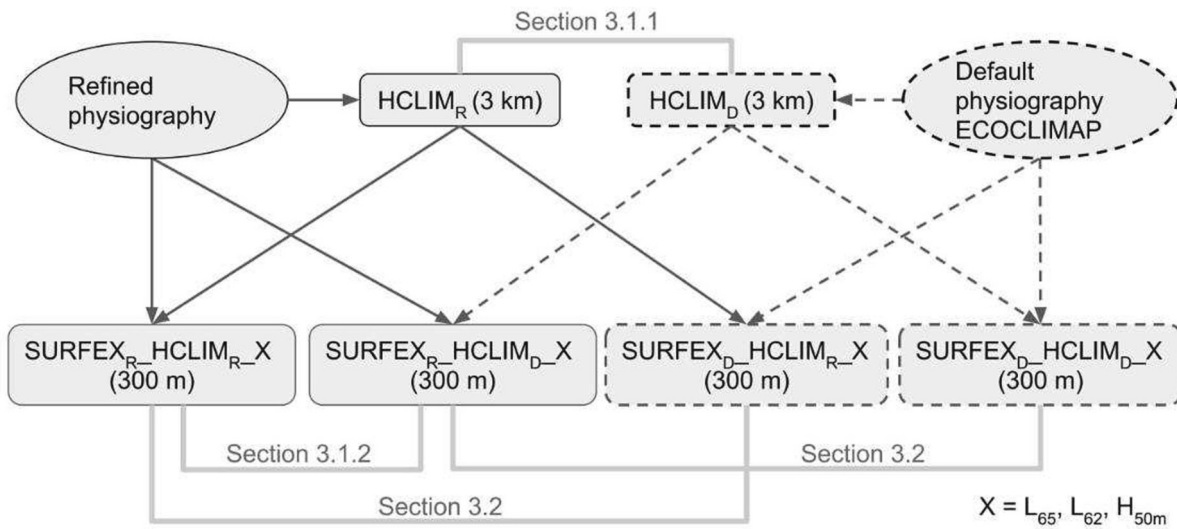


Fig. 2. The schematic of the simulations. Dashed and solid lines indicate default and refined physiography, respectively. For simplicity, we refer to the offline coupled SURFEX simulations as SURFEX. The experiments compared in different sections are indicated by thick grey lines.

3.1. The impacts of atmospheric forcing on SURFEX simulations

Here we address the first of our research questions: ‘How sensitive is the LSM T2m to different CPM forcing?’

3.1.1. Comparison of air temperature simulated by HCLIM with different physiography

Since HCLIM outputs in this study are used only as forcing for the offline SURFEX simulations, we refer to them as HCLIM (or atmospheric) forcing. To evaluate the change in HCLIM forcing resulting from different physiography, Fig. 3 compares the simulated monthly mean air temperatures at the model level 65 (Figs. 3a–3b), at the height of 50 m (Figs. 3c–3d), and at the model level 62 (Figs. 3e–3f) between HCLIM_R and HCLIM_D. Because the main focus of the study is on air temperature over land, the results in both HCLIM and SURFEX are masked out over the sea. The HCLIM_R simulation results in higher air temperature than HCLIM_D over most regions. After masking out the sea surfaces, the difference in air temperature is mainly found over urban areas, where the larger changes in physiography are present. The process of urbanising or densifying a particular area has different impacts on the microclimate depending on the changes considered (in particular the grey-to-green ratio) some of which possibly counteracting each other. Therefore, the air temperature changes shown here integrate the full complexity of the processes involved.

There are also differences in air temperature over areas with small or no change in physiography as a consequence of horizontal transfer in the atmospheric model. Such differences in the HCLIM variables (used as forcing to SURFEX) are then transferred to SURFEX offline simulations (see section 3.1.2).

In general, the difference in temperature decreases with the increase of height due to a weakening of surface-induced atmospheric perturbations at higher altitudes. This decrease is considerably smaller for daytime conditions because of the stronger vertical mixing. The largest difference of monthly mean air temperature is as high as 1 K and is found at night in the lowest level of the HCLIM simulations. The larger nighttime difference is explained by a better representation of urbanised areas in the refined physiography and the resulting intensification of the UHI effect. This effect is most apparent over the metropolitan area of Stockholm, but also over smaller cities surrounding it such as Södertälje in the southwest, Uppsala in the northwest, and Norrtälje in the northeast along the coast.

3.1.2. Comparison of T2m simulated by SURFEX with different atmospheric forcings

The T2m differences between each pair of SURFEX_R offline simulations (SURFEX_R-HCLIM_D and SURFEX_R-HCLIM_R) forced by atmospheric data at three different levels; Fig. 4) are larger than the air temperature differences between the corresponding HCLIM forcing simulations (HCLIM_R and HCLIM_D). The difference in T2m obtained with SURFEX offline simulation decreases with the increase of atmospheric forcing level, as expected.

As already noticed in Fig. 3, the forcing height has a much smaller impact on the daytime than on nighttime results (Fig. 4) due to the daytime enhanced vertical mixing. Moreover, by comparing the results between HCLIM_R and HCLIM_D, we find that the differences in T2m are larger than the differences in air temperature at L₆₅, L₆₂ and H_{50m} (not shown). This is consistent with the differences in HCLIM air temperatures (at L₆₅, L₆₂ and H_{50m} in Fig. 3) being enhanced in T2m simulated by SURFEX (Fig. 4) during the day and almost over the whole domain.

Over the northern region of the domain, despite the relatively small surface refinement (Figs. 1b–1c), temperature changes larger than 0.5 K can be found with a distinct patchy pattern, especially during the day (Fig. 4). There is a clear signal over the Stockholm archipelago (both in day- and nighttime) and over the city (during night). The difference over the northern part of the domain also

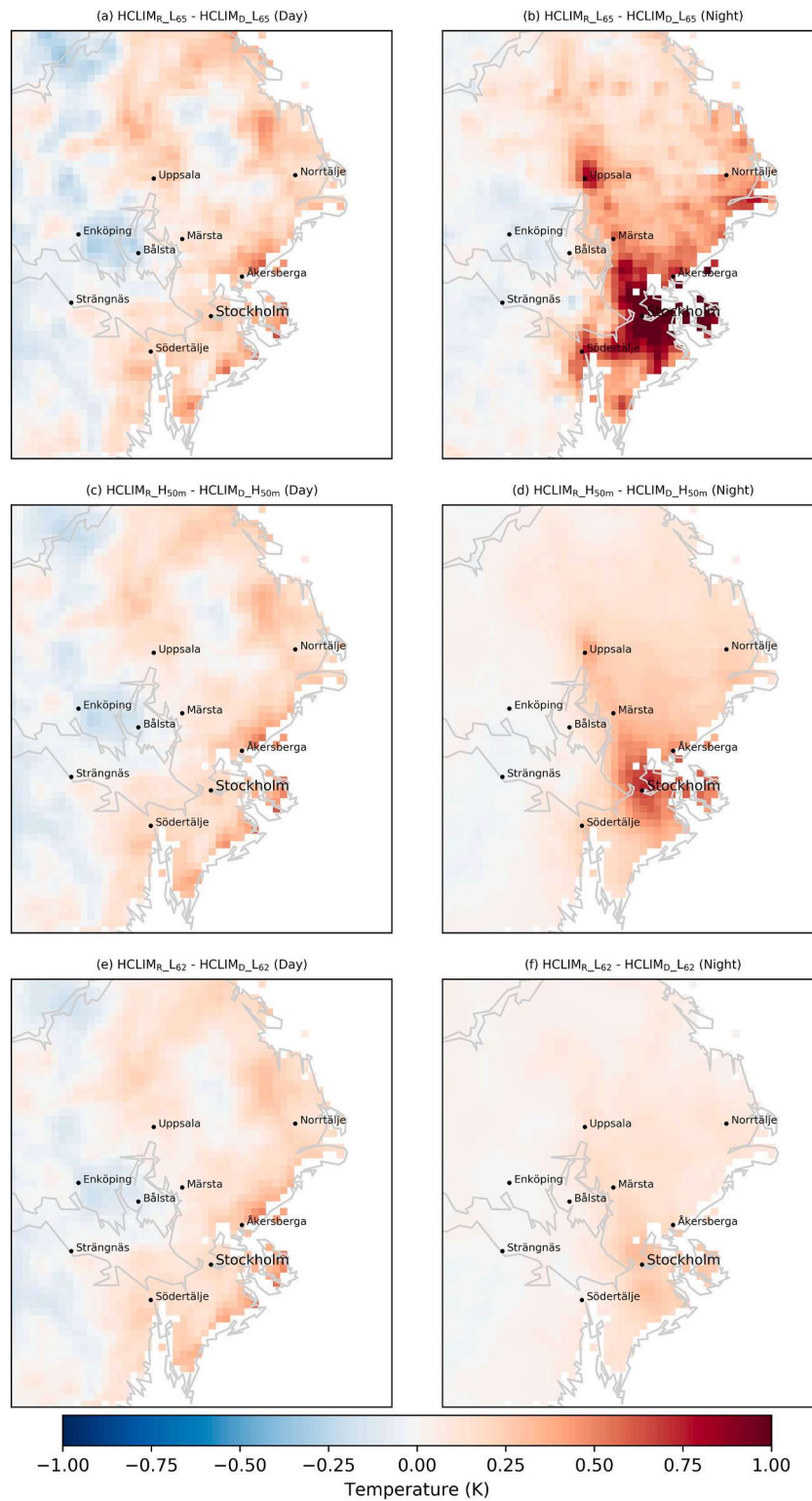


Fig. 3. Monthly average difference in air temperature (unit: K) between HCLIM_R and HCLIM_D at different heights during day (15:00–18:00) and night (0:00–3:00).

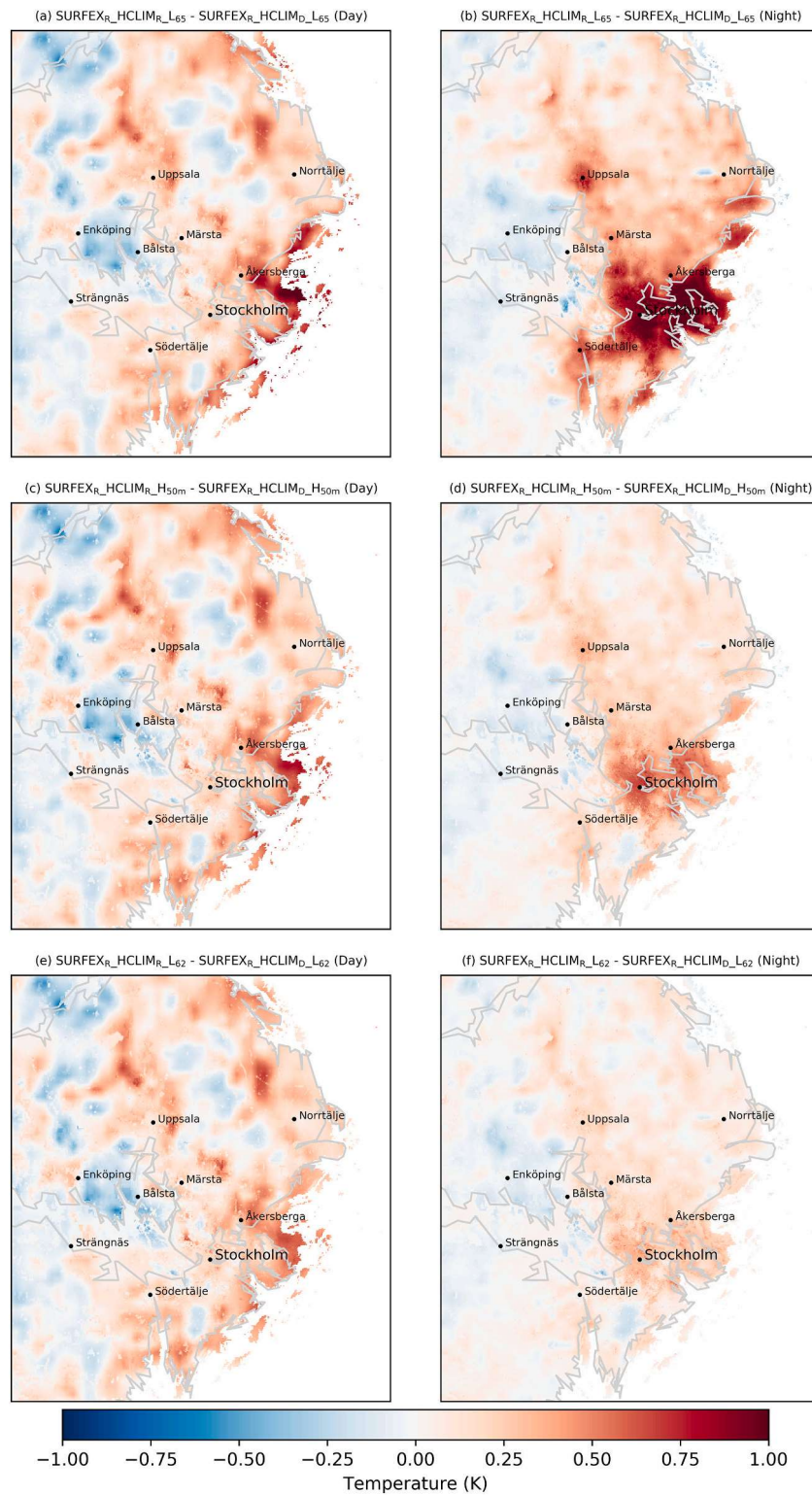


Fig. 4. Monthly average T2m difference (unit: K) between SURFEX_R_HCLIM_D and SURFEX_R_HCLIM_R as forced by HCLIM atmospheric data at different levels/heights during day (15:00–18:00) and night (0:00–3:00).

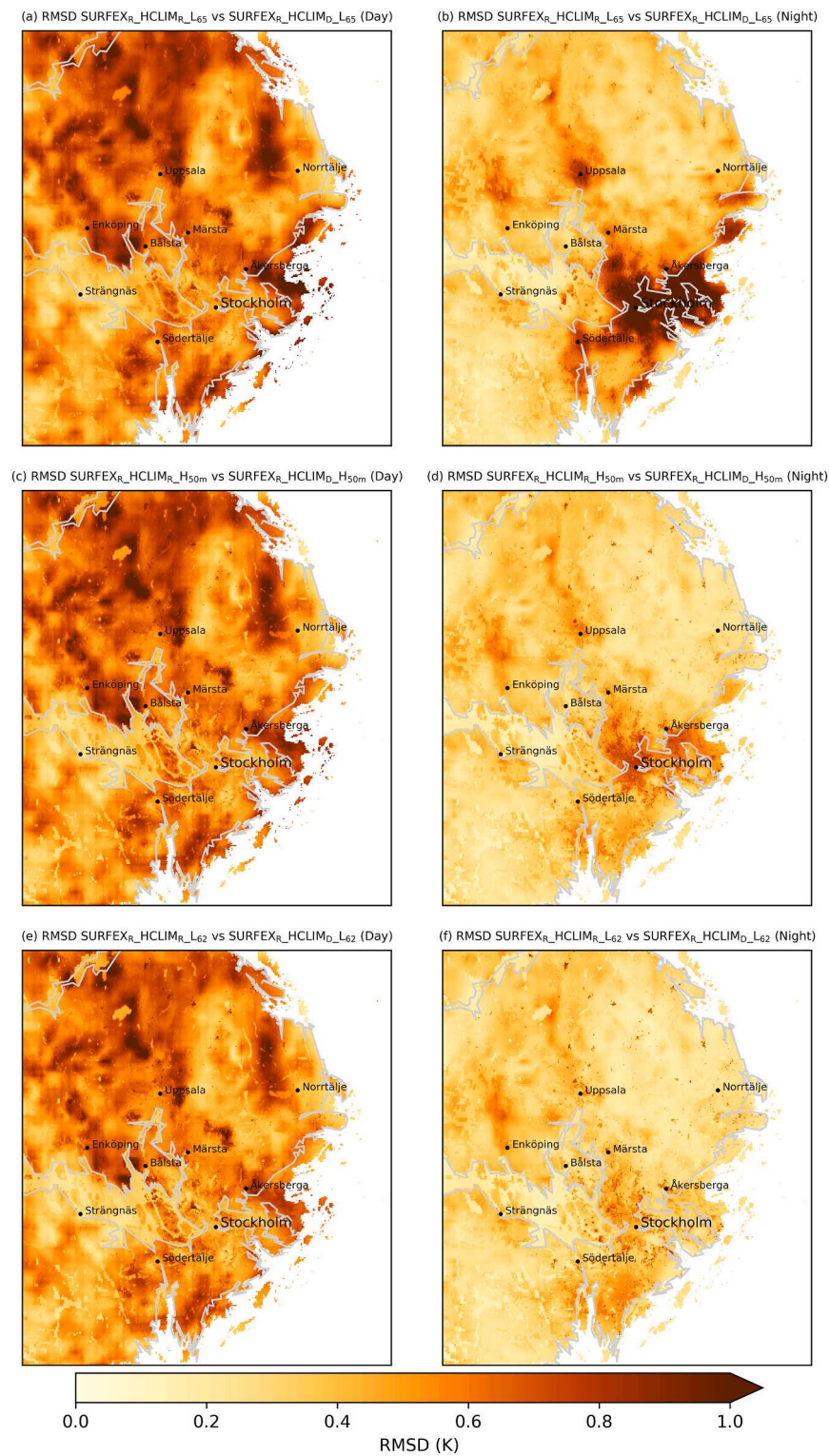


Fig. 5. The RMSD for T2m (unit: K) between SURFEX_R_HCLIM_D and SURFEX_R_HCLIM_R as forced by HCLIM atmospheric data at different levels or heights: the lowest atmospheric level L₆₅ (a, b), H_{50m} (c, d) and L₆₂ (e, f). Left for daytime (15:00–18:00), and right for nighttime (0:00–3:00). The RMSD is computed over each grid point using hourly T2m values over July 2018.

exists in the HCLIM simulations (Fig. 3a), although the physiography changes are small (Fig. 1b). Unlike HCLIM simulations (section 3.1.1), there are no lateral exchanges in SURFEX offline simulations. Since the two experiments SURFEX_RHCLIM_D and SURFEX_RHCLIM_R share the same high resolution physiography, the regions affected in Fig. 4 correspond to the grid points having different air temperature forcing in Fig. 3. The signal observed over the north is from the difference in HCLIM atmospheric forcing.

In order to understand the significance of the differences in T2m, we calculated RMSD for each model grid point for each pair of SURFEX experiments. During nighttime, high RMSD (Figs. 5b and 5d) is found over regions with considerable changes in physiography (Figs. 1b and 1c). During daytime (Figs. 5a, 5c and 5e), high RMSD is found over many parts of the domain, which could be explained by the stronger vertical mixing and horizontal advection. We further applied a *t*-test of T2m difference for each pair of SURFEX simulations (Fig. A1). The *t*-test indicates that the T2m difference is significant only over a few grid points near the archipelago for SURFEX_RHCLIM_RL₆₅ and SURFEX_RHCLIM_DL₆₅ over nighttime. The difference is not significant for model level L₆₂ and H_{50m} over the study domain. The same *t*-test results were obtained for air temperature differences at L₆₂, L₆₅ and H_{50m} simulated by HCLIM (Fig. A2). The spatial distribution patterns of the *P* values between SURFEX (Figs. A1a–A1b) and HCLIM results (Figs. A2a–A2b) are consistent. This indicates that the differences are not related to systematic physiography differences, but to the atmospheric forcing.

In the above SURFEX experiments, the impacts of different forcing heights and forcing values are mixed in the comparison of SURFEX results. We further applied the same forcing data from HCLIM output artificially at different levels/heights in order to understand if the T2m differences between different SURFEX simulations come from the prescribed forcing height or from the differences present in the HCLIM outputs. Specifically, we performed two additional simulations: SURFEX_RHCLIM_RH_{50m}toL₆₅, which has the same set-up as SURFEX_RHCLIM_RH_{50m} except that the forcing data at H_{50m} was used at level L₆₅; and SURFEX_RHCLIM_RL₆₅toH_{50m}, which has the same set-up as SURFEX_RHCLIM_RL₆₅ but the forcing data at L₆₅ was used at level H_{50m}. Both SURFEX_RHCLIM_RH_{50m}toL₆₅ and SURFEX_RHCLIM_RL₆₅toH_{50m} simulations were compared with SURFEX_RHCLIM_RH_{50m}. Figs. A3a and A3b show the impacts of forcing level/height on SURFEX simulation, while Figs. A3c and A3d show the impacts of HCLIM outputs (or forcing data) on SURFEX simulations. Results show that each factor (prescribing the right forcing height, or the correct model output) impacts T2m with approximately the same magnitude. It indicates that both factors are important for SURFEX offline simulations.

In summary, the impacts of different atmospheric forcing obtained from HCLIM simulations (with different physiography) on T2m simulated by the SURFEX LSM decrease with the increase of atmospheric forcing height. The difference in the SURFEX T2m forced by two HCLIM experiments with different physiography becomes non-significant over the whole domain when forced by atmospheric data at a height of H_{50m} or above.

3.2. The impacts of physiography change on SURFEX simulations

Here we address the second of the two questions from Introduction, namely ‘How sensitive are the effects of physiography changes on T2m to different CPM forcing?’. In the previous section, the refined physiography data was used in all SURFEX offline simulations, while here we investigate the impacts of physiography changes in SURFEX offline simulations.

Figs. 6a–6b show the day/nighttime difference in T2m between SURFEX_RHCLIM_DH_{50m} and SURFEX_DHCLIM_DH_{50m} (both forced by HCLIM_D at 50 m height). For most regions, the T2m simulated with refined physiography is higher. This is consistent with the results from HCLIM where SURFEX is used in coupled mode (Fig. 3). The T2m differences in the night (reaching 1 K) are generally larger than in the day (maximum value of around 0.5 K), but they are all consistent with the physiography changes and have the largest differences over the newly urbanised areas (i.e., those defined as natural landscapes in ECOCLIMAP and converted into built-up areas during the refinement process). Conversely, the negative changes in SURFEX_RHCLIM_DH_{50m} on land are mostly located over points where the urban fraction was substituted with a corresponding nature fraction in the refined physiography. The negative change in SURFEX_RHCLIM_DH_{50m} around the archipelago in the eastern part of the domain during the day (Figs. 6a) is due to an increase in nature fraction and decrease in sea fraction (Figs. 1c and A4).

Similar results are found when SURFEX is forced by HCLIM_R in Figs. 6c–6d. This is further confirmed by the consistent spatial patterns of the RMSD (Fig. 7). The spatial Pearson correlation coefficients of RMSD between Figs. 7a and 7c (daytime) and between Figs. 7b and 7d (nighttime) are higher than 0.98 (Table 2). The correlation coefficient between RMSD and the change in tile fractions is higher than 0.75 during daytime and higher than 0.83 at nighttime (Table 2). This result is consistent with the significance test (*t*-test) result (Fig. A5). Generally, the regions where the T2m difference is statistically significant ($P \leq 0.05$, in brown) are the regions with highest physiography changes (Fig. 1b). The absolute values of correlation coefficients between the *P*-value and the change of tile fractions are higher than 0.31 over the day and higher than 0.75 over the night (Table 2).

These results are expected because the impacts of different air temperature forcing on SURFEX simulations are negligible at the forcing height of 50 m or above (in Section 3.1.2). However, these conclusions do not change even when using atmospheric forcing at levels L₆₅ (~12.5 m, Figs. A6–A8) or L₆₂ (~90 m). This implies that the effects of physiography changes on T2m changes in SURFEX offline simulations are not sensitive to different atmospheric forcing data with different physiography. In summary, the T2m differences between offline SURFEX simulations using different physiography are highly correlated, regardless of the physiography used in the HCLIM forcing or the HCLIM forcing height.

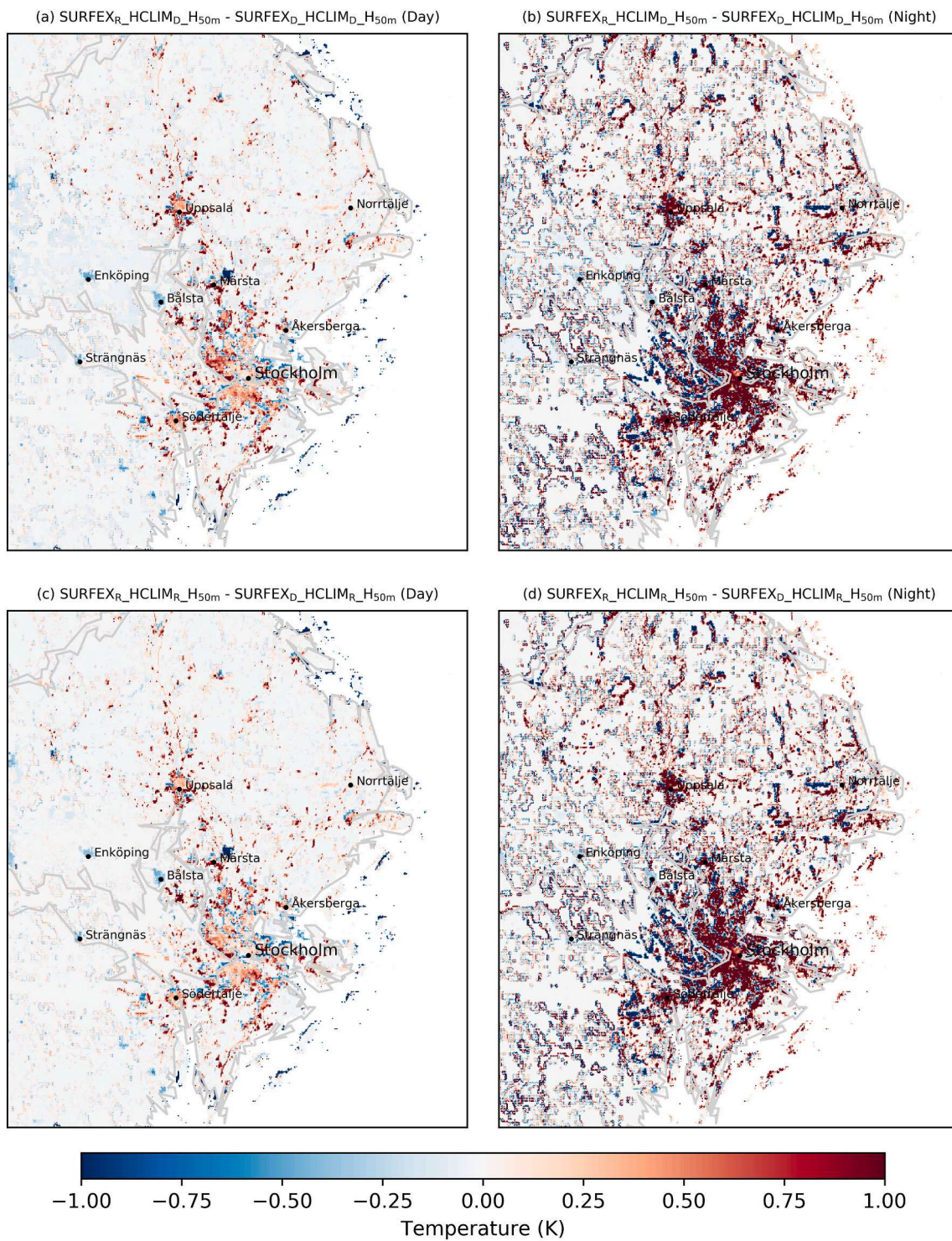


Fig. 6. Monthly average difference in T2m (unit: K) between SURFEX_R_HCLIM_D_H_{50m} and SURFEX_D_HCLIM_D_H_{50m} (a, b), and between SURFEX_R_HCLIM_R_H_{50m} and SURFEX_D_HCLIM_R_H_{50m} (c, d) during day (15:00–18:00, left) and night (0:00–3:00, right).

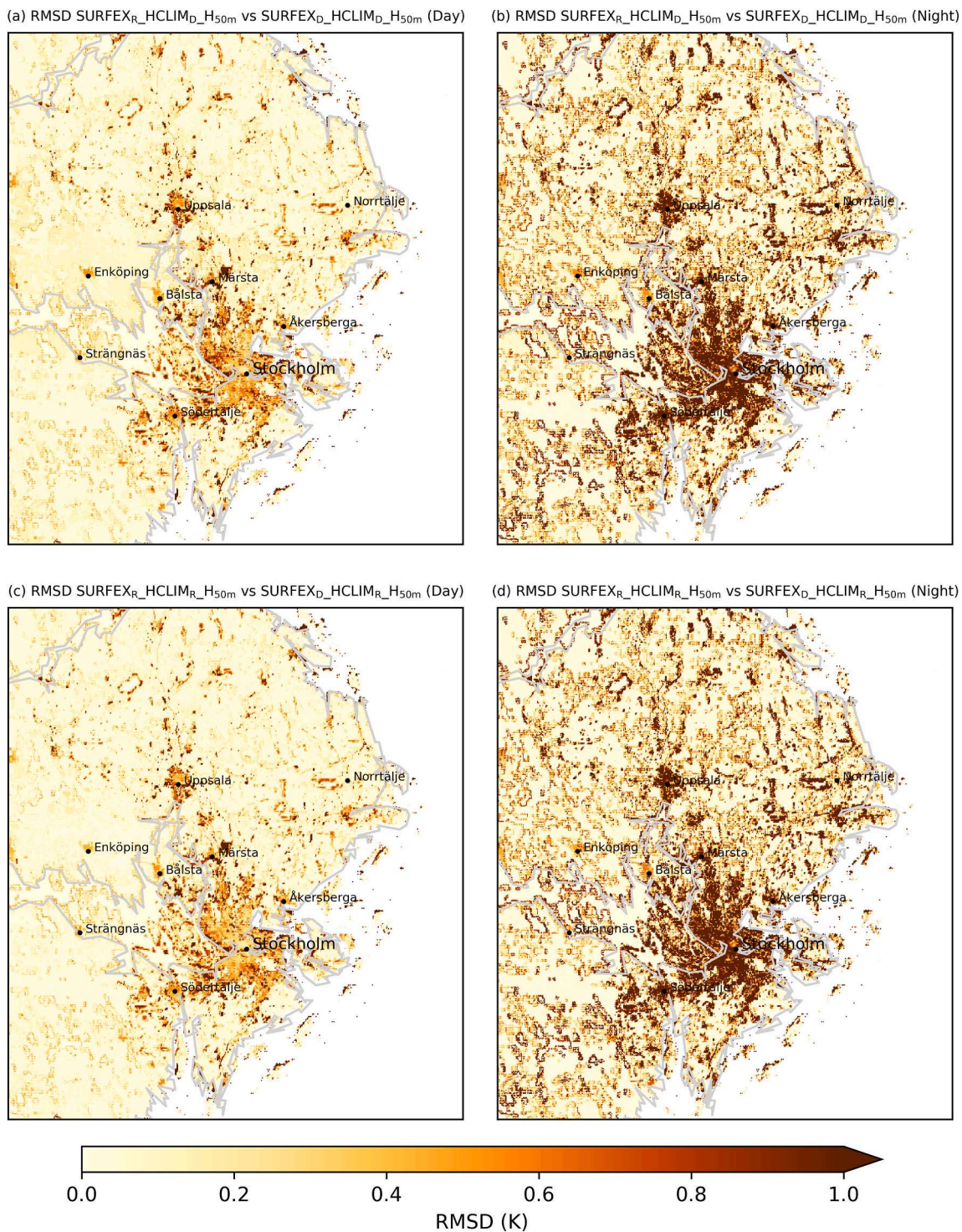
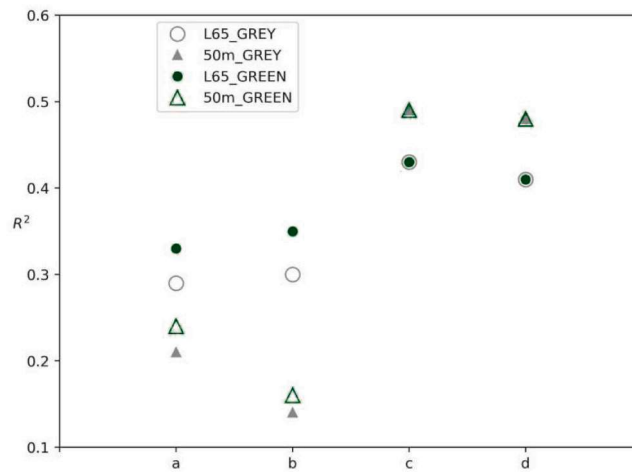


Fig. 7. The RMSD for T2m (unit: K) between SURFEX_R_HCLIM_D and SURFEX_D_HCLIM_D (a, b) and between SURFEX_R_HCLIM_R and SURFEX_D_HCLIM_R (c, d), with the atmospheric forcing for all simulations being at 50 m above buildings. Left for daytime (15:00–18:00), and right for nighttime (0:00–3:00). The RMSD is computed over each grid point using hourly T2m values over July 2018.

Table 2

The spatial Pearson correlation coefficients for RMSD and P-value of t-test between different SURFEX simulations and physiography changes.

Two sets of experiment data used to compute Pearson correlation coefficient (r)		Model level / Height	r	
			Day	Night
RMSD of T2m for SURFEX _R HCLIM _D vs SURFEX _D HCLIM _D	RMSD of T2m for SURFEX _R HCLIM _R vs SURFEX _D HCLIM _R	L ₆₅	0.9896	0.9976
		H _{50m}	0.9892	0.9991
		L ₆₂	0.9909	0.9992
Fraction change	RMSD of T2m for SURFEX _R HCLIM _D vs SURFEX _D HCLIM _D	L ₆₅	0.7659	0.8330
		H _{50m}	0.7808	0.8852
		L ₆₂	0.8008	0.8987
Fraction change	RMSD of T2m for SURFEX _R HCLIM _R vs SURFEX _D HCLIM _R	L ₆₅	0.7582	0.8310
		H _{50m}	0.7849	0.8877
		L ₆₂	0.8025	0.8999
P-value of t-test for T2m of SURFEX _R HCLIM _D vs SURFEX _D HCLIM _D	P-value of t-test for T2m of SURFEX _R HCLIM _R vs SURFEX _D HCLIM _R	L ₆₅	0.8990	0.9622
		H _{50m}	0.9078	0.9831
		L ₆₂	0.9115	0.9841
Fraction change	P-value of t-test for T2m of SURFEX _R HCLIM _D vs SURFEX _D HCLIM _D	L ₆₅	−0.3148	−0.7510
		H _{50m}	−0.3867	−0.7773
		L ₆₂	−0.4626	−0.7803
Fraction change	P-value of t-test for T2m of SURFEX _R HCLIM _R vs SURFEX _D HCLIM _R	L ₆₅	−0.3368	−0.7569
		H _{50m}	−0.3689	−0.7800
		L ₆₂	−0.4528	−0.7828



X-axis	Physiography field	Temperature field (corresponding figure)	Resolution
a	HCLIM _R - HCLIM _D	HCLIM _R - HCLIM _D (Figs. 3b & 3d)	3 km
b	HCLIM _R - HCLIM _D	SURFEX _R HCLIM _R - SURFEX _R HCLIM _D (Figs. 4b & 4d)	3 km
c	SURFEX _R - SURFEX _D	SURFEX _R HCLIM _R - SURFEX _D HCLIM _R (Figs. 6d & A6d)	300 m
d	SURFEX _R - SURFEX _D	SURFEX _R HCLIM _D - SURFEX _D HCLIM _D (Figs. 6b & A6b)	300 m

Fig. 8. The coefficients of determination (R^2) of the changes in T2m fields in relation to the corresponding changes in the spatial variation of land cover. The results correspond to the nighttime (0:00–3:00 local time), when the surface effect and correlation are stronger. ‘GREY’ and ‘GREEN’ include, respectively, all impervious and vegetated surfaces, which in the refined physiography account for the fraction of urban vegetation (identified as ‘GARDEN’ in SURFEX). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Relationship between physiography and temperature in HCLIM and SURFEX offline

The modelled response of air temperature to the changes imposed on physiography, and how these propagate from the larger scale model to the LSM, is further analysed. Fig. 8 shows the coefficients of determination (R^2) relating the changes in physiography with the corresponding difference in air temperature for the simulation sets presented in the previous sections. The results are plotted according to the forcing height and the land cover type. The relationship is assessed considering the spatial variation of surface cover as interpolated and used by HCLIM and SURFEX offline, respectively on 3 km and 300 m grid spacing. The calculation of R^2 in case (a) in Fig. 8 uses the HCLIM temperatures at two specified levels (L_{65} and H_{50m}) that constitute the forcing for SURFEX offline, while for the other cases, R^2 is calculated using the SURFEX offline T2m from experiments with different atmospheric forcings. For testing the differences in HCLIM forcing, the SURFEX offline results were interpolated to the HCLIM 3 km grid in case (b). For testing the differences in physiography, the SURFEX offline results were kept at the original 300 m grid for cases (c) and (d). For simplicity, the values refer to nighttime temperature only. Only grid cells with a fraction of freshwater and/or sea below 5% were considered to avoid introducing the effect of water bodies on the weighted average of the tiles temperature.

Fig. 8 shows that, while in SURFEX offline experiments at 300 m resolution (cases c and d) the change in air temperature responds similarly over 'GREEN' and 'GREY' surfaces, the variability of modelled temperature at 3 km grid spacing (cases a and b) is better predicted from changes in vegetation than from those in impervious surfaces. This behaviour is explained by the weaker capacity of the 3 km resolution model to capture the heterogeneities of the urban surface, than over large forest areas. Also the lake Mälaren shoreline, which was heavily refined, is only roughly captured by the coarser-scale model.

For the HCLIM temperature fields at different levels, which are used as forcing for the SURFEX offline simulations, the relationship between the changes in temperature and physiography expectedly decreases with height (Fig. 8, case a). The physiography signature from the HCLIM forcing simulations propagates to the SURFEX offline T2m when the forcing is closer to the surface (L_{65}), but the signature is lost for the higher-level forcing (H_{50m}) (Fig. 8 case b).

The cases (c) and (d) in Fig. 8 show that the contribution of HCLIM atmospheric forcing to the differences in T2m is very small compared to the contribution of physiography changes in the higher resolution model. Additionally, the R^2 for these two sets of simulations is higher (in the range 0.4–0.5) than for the other cases, supporting the assumption that SURFEX offline predominantly responds to changes in its local physiography. This is further confirmed by the small difference in R^2 between cases (c) and (d), i.e. between the effects of the different physiography used in the forcing model.

Fig. 9 depicts the relationship between the changes in the vegetation fraction and nighttime T2m as simulated by SURFEX offline. In this case, and unlike Fig. 8, all grid points were considered independently from the fraction of water. The linear regression shows that 59% of the T2m difference is explained by the changes in the vegetation fraction ('GREEN') between the original ECOCLIMAP database and the refined physiography. As an indication of the cooling of the urban atmosphere by vegetated areas, the regression indicates a decrease of the nighttime T2m by 0.34 K per 10 percentage points of increase of fraction in the 'GREEN' coverage. The Pearson correlation coefficient (r) of -0.77 reveals a reasonably strong negative linear relationship between the two variables, which decreases

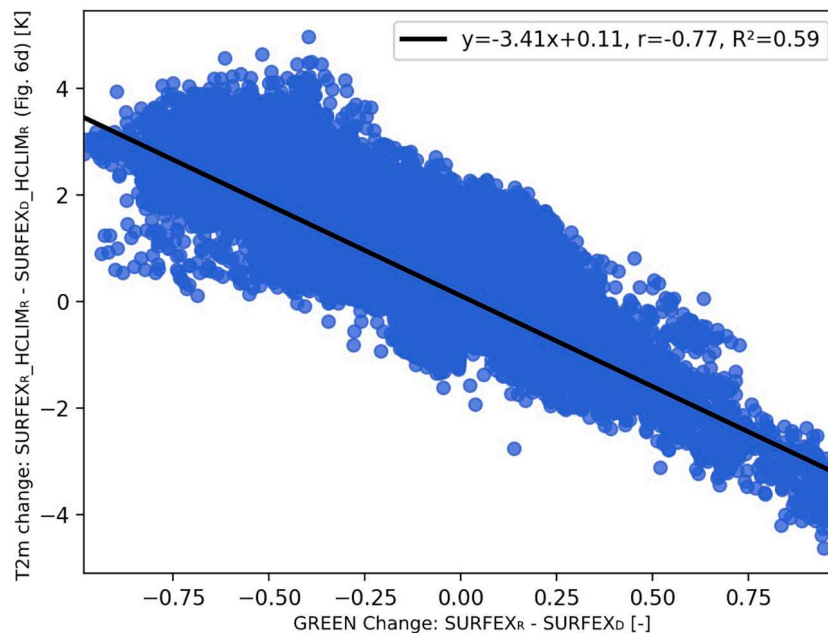


Fig. 9. Scatter diagram with regression line of the difference in GREEN fraction (on the 300 m resolution grid) in relation to the corresponding difference in nighttime T2m between SURFEX_R and SURFEX_D using the same forcing HCLIM_R at H_{50m} (Fig. 6d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during daytime (not shown) due to the nocturnal prevalence of the UHI. Moreover, differences in T2m as high as ± 4 K were modelled as a result of the greening/urbanisation of the surface, therefore highlighting the importance of accurate physiography when downscaling the urban climate to spatial resolutions of 1 km or higher.

4. Conclusions

This study aims to assess the feasibility of simulating the urban climate at high resolution with the offline SURFEX LSM using locally refined physiography data and forced by the HCLIM CPM using default coarser physiography data. The refined dataset is characterised by 107.6% greater built-up area over the Stockholm region than the default physiography ECOCLIMAP 2.2, and also a more accurate definition of building height based on laser scanning data. Depending on the purpose, SURFEX is forced by HCLIM atmospheric data at different heights above buildings. Two questions were addressed:

- (1) How sensitive is the LSM T2m to different CPM forcing? As expected, the increase of urban fraction in the refined physiography in CPM leads to higher air temperature. This effect decreases with increasing model height in the CPM. As a result, the effect of different CPM forcing on LSM T2m decreases when using CPM forcing from higher levels. Furthermore, prescribing the CPM forcing at a higher height in the LSM additionally reduces the effect of the different CPM forcing. These two effects (higher CPM forcing level and prescribing forcing at a higher height in LSM) combine and result in an even smaller effect of the different physiography on the LSM T2m as the forcing height increases. The impact of the different physiography stops being statistically significant when the forcing level from the parent CPM is 50 m or above. Using the CPM forcing at lower levels, the impact of a different forcing-model physiography on the T2m simulated by the offline SURFEX LSM can be as high as 1 K over the urban area (with atmospheric forcing at L65, about 12.5 m above buildings).
- (2) How sensitive are the effects of physiography changes on T2m simulations to CPM forcing? The results show that the spatial patterns of the changes in T2m are highly correlated with the changes in the SURFEX LSM physiography, even if using different physiography in atmospheric forcings. However, the magnitude of the T2m changes in SURFEX simulation can be slightly different when using atmospheric forcings with different physiography or at different forcing heights. The correlation coefficient between SURFEX physiography-change-caused T2m differences using different atmospheric forcing can be as high as 0.98.

Therefore, the main results can be summarized as follows: (1) When simulating the urban T2m with LSM at high resolution, the same physiography in the CPM forcing data and the LSM should be used for lower forcing heights (i.e. below 50 m), but the physiography can be different if the forcing is high enough (i.e. above 50 m in our example). (2) When simulating the effects of physiography refinement in LSM on the urban T2m, the CPM forcing with different physiography can be used at any height.

Furthermore, according to our modelling results, the physiography refinement can cause considerable T2m effects (0.5 K during the day and 1 K during the night) depending, among other factors, on the intensity/extension of the surface changes and time of the day. The refined physiography data was tested by using the numerical weather prediction system HARMONIE-AROME and validated against several station observations over Stockholm by [Gidhagen et al. \(2020\)](#) and [Amorim et al. \(2020\)](#). These studies showed that the model simulations using the refined physiography performed well in simulating seasonal and diurnal variations of air temperature. Aiming at a detailed understanding of the spatial variability of air temperature over a city, current default physiography databases (e.g., ECOCLIMAP 2.2) may require additional refinement with local surface data.

The method proposed in this study can be extended to other similar application cases. Local climate adaptation frequently needs reliable future climate information at high resolutions. Assuming similar magnitude of physiography changes to those presented in this study, this method provides the opportunity to study the urbanisation impacts on air temperatures at high resolution (hundreds of meters) using offline LSM forced by the available CPM simulations at coarser scale (kilometer scale) for different climate change and urban development scenarios. Further studies are needed to evaluate more variables, different forcing magnitudes and heights, and to implement this methodology over other domains and over longer simulation periods.

CRediT authorship contribution statement

Fuxing Wang: Conceptualization, Data curation, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Danijel Belušić:** Methodology, Formal analysis, Supervision, Conceptualization, Writing - review & editing. **Jorge H. Amorim:** Methodology, Formal analysis, Visualization, Supervision, Funding acquisition, Conceptualization, Project administration, Writing - review & editing. **Isabel Ribeiro:** Methodology, Conceptualization, Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.uclim.2023.101531>.

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