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Assessing urban slab model parameterization in the global ICON-NWP

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With 6 figures and 1 table

Abstract: Urban areas can strongly influence mesoscale atmospheric processes in its surroundings. Despite over 55% of the world's population living in urban areas, the integration of urban parameterizations into national meteorological and hydrological service models has only recently begun. The incorporation of an urban representation within numerical weather prediction (NWP) models is assumed to have the potential to enhance the forecast accuracy and to provide an improved data basis for urban planning. In this study, We investigate the applicability of the urban slab model TERRA_URB to the global operational ICON-NWP at the German national meteorological service with 13 km resolution by simulating two five-day periods in July 2021 and June 2022. The ICON model is a widely used modeling framework but in its operational global configuration, urban areas are represented solely as a distinct soil type. The June 2022 simulation period is characterized by synoptical conditions favorable for a strong urban heat island development, while July 2021 is characterized by more overcast conditions, including several precipitation events. A comparison with 2 m air temperature observations from the urban climate station in Berlin, Alexanderplatz, revealed reduced root mean square errors when including TERRA_URB in ICON-NWP by 26% (from 1.9 to 1.4 for a five-day lead time in July 2021, and from 4.2 to 3.1 in June 2022). The implementation of TERRA_URB thus results in a quantifiable improvement in the global ICON-NWP runs, with results that are closer to the theory of urban climate. The study finds that urban weather forecasts are less accurate under strong than weak canopy urban heat island conditions, indicating room for improvement.

Keywords: ICON-NWP; TERRA_URB; urban heat island; urban meteorology; slab model parameterization

1 Introduction

Global urbanization has implications not only in socio-economic terms but also for our weather and climate, as cities modify wind currents, radiation, water and energy balances of the Earth's surface and thus cause a specific urban climate (Oke et al. 2017). Today, more than 55% of the world's population lives in urban areas, and the United Nations projects that this number will increase to 68% by 2050 (United Nations Department of Economic and Social Affairs 2018). This increase in urban population leads to further expansion of urban areas. Mahmood et al. (2014) states that this process represents "one of the most intense and multifaceted alterations of the landscape for its comparable spatial scale". According to the IPCC's Sixth Assessment Report, urbanization processes, especially in combination with the threats associated with climate change, are with *high confidence* increasing the vulnerability and exposure of cities. Such hazards include heat waves, flooding, storms, and sea level rise (Dodman et al. 2022). The report also indicates that the slow adoption of monitoring and assessment frameworks limits the potential to develop climate-resilient urban development pathways (*medium confidence*).

Given that the majority of the world's population lives in urban areas, their consideration in weather and climate models is of great relevance. Depending on the spatial extent and resolution, weather and climate models can be categorized as global, regional, or convection-permitting. In general it can be assumed that a larger model domain comes with a lower spatial and temporal resolution. Global Earth System Models (ESMs) simulate the entire Earth system and are able to represent large-scale climate processes. Regional Climate Models (RCMs) can be applied to dynamically downscale the ESM output to achieve a higher resolutions, as done in the Coordinated Regional Climate Downscaling Experiment (CORDEX) (e.g., Jacob et al. (2014)). A further development

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are convection-permitting models which operate at even finer resolutions (≤ 4 km), allowing for the explicit simulation of convection (Prein et al. 2015). Processes that cannot be explicitly resolved at a given grid spacing must be parameterized. The subscale processes that need to be parameterized typically include radiation and cloud microphysics (Knoche & Keuler 2017). In general it can be said that the higher the resolution, the fewer parameterisations are needed.

To account for a more realistic representation of urban areas in models, urban parameterization schemes have been developed. These urban schemes can be classified as slab models, single-layer urban canopy models (SLUCMs), or multi-layer urban canopy models (MLUCMs). Slab models are the simplest category, as they do not resolve individual urban structures but instead combine the built land cover into one tile. Lipson et al. (2024) conclude that slab models generally perform well, particularly when combined with sophisticated hydrological and vegetation land surface models. In contrast, urban canopy models can explicitly represent the urban canyon geometry, resolving the city in 3D by dividing it into rooftops, walls, and streets. Here, SLUCMs include a single vertical plane, whereas MLUCMs consider several vertical layers (Tarasova et al. 2023). Only recently, the integration of urban parameterization has begun into national meteorological and hydrological service models. When considered, it is typically at a 1–4 km resolution (Lipson et al. 2024; Schlünzen et al. 2023). At the German national meteorological service (DWD), the implementation of the slab model TERRA_URB has started in 2025 and is currently limited to the regional operational convection permitting ICON-D2 (Icosahedral Nonhydrostatic Model). The European Center for Medium-range Weather Forecast (ECMWF) incorporated a SLUCM within their Integrated Forecast System (IFS) at a global resolution of 9 km, which has been operational since November 2024.

A central motivation for including urban parameterizations in weather and climate models is their ability to represent key urban climate phenomena, most notably, the urban heat island (UHI) effect. The UHI is one of the most prominent features distinguishing urban from rural areas. It results from changes in the energy balance due to urban land properties, leading to higher temperatures, increased heat stress, and altered heating and cooling behaviors. The UHI phenomenon can be divided into four types, each with different causes and spatial and temporal characteristics: subsurface, surface, canopy, and boundary layer UHI. The canopy urban heat island (C-UHI) is the best studied and exhibits a clear diurnal pattern. It is typically assessed using 2 m air temperature data. The C-UHI is vertically defined by the height of urban elements such as buildings and vegetation and corresponds to the atmospheric layer most experienced by humans. Its well-understood behavior and strong diurnal cycle make it particularly suitable for assessing the influence of urban parameterizations. The C-UHI tends to be strongest at night, especially under dry soil moisture conditions in rural areas, as well as overall low wind speeds and clear skies Another important urban-related phenomenon is the urban plume, which refers to the downwind transport of warm, often polluted air from cities into surrounding rural regions. Urban plumes typically extend tens to hundreds of kilometers and are thus classified as mesoscale phenomena (Oke et al. 2017).

In regional modeling, TERRA_URB has been extensively used as a slab urban parameterization scheme to improve the representation of urban thermal effects. TERRA_URB developed for the COSMO (Consortium for Small-scale Modeling) regional atmospheric model is described in Wouters et al. (2015, 2016). The same authors assessed the integration of TERRA_URB in COSMO-CLM (COSMO model in CLimate Mode) for Belgium at a 2.8 km resolution centered around Brussels. Compared to the reference run, simulations with TERRA_URB exhibit a maximum 2 m temperature difference of 2 K at night and a minimum differences around noon. Similarly, Garbero et al. (2021) evaluated TERRA_URB for Turin, Naples, and Moscow at 1 km resolution. In both studies, the urban scheme improved the air temperature forecasts and captured a diurnal UHI cycle as expected from theory. Further applications of TERRA_URB included simulations with COSMO-CLM in Moscow (Rivin et al. 2020), Berlin (Trusilova et al. 2016), and a tropical residential neighborhood in Singapore (Demuzere et al. 2017). The COSMO Priority Project CITTA (City Induced Temperature change Through Advanced Modelling) implemented TERRA_URB in the ICON model (Schulz et al. 2022). Campanale et al. (2025) evaluated this implementation for August 2017 for the Italian cities Milan and Rome at a horizontal resolution of 2 km. The study demonstrated a successful integration of TERRA_URB into ICON and a reasonable representation of the UHI.

Validating urban 2 m temperature in models is challenging due to the limited number of official urban climate stations. The DWD operates six such stations in Berlin, Freiburg, Hanover, Dresden, Regensburg, and Hamburg (DWD 2024). However, as of June 2024, these stations are not assimilated in the ICON-NWP system. New urban monitoring networks such as ICOS Cities (Integrated Carbon Observation System) and Urbisphere have recognized this limitation and are working on establishing denser urban measurement networks across multiple cities in Germany and internationally (ICOS 2024; Urbisphere 2024). ICOS Cities, for example, involves a network of around 15 German cities and conducts intensive observation periods (IOPs) to collect detailed urban climate data. With the same aim, Urbisphere focuses on several European, African, and Asian cities. While the IOPs provide valuable insights, they are limited to specific campaigns and cannot replace the need for continuous long-term observations. Recent developments also include crowd-sourcing approaches to urban climate measurements (Masson et al. 2020).

While high-resolution models are essential to capture the heterogeneity of urban areas, there is also a growing need to understand how urban processes can be represented in coarser ESMs. Firstly, several studies show that urban areas significantly influence the regional climate (Katzfey et al. 2020; Liu & Niyogi 2019), and an improved urban parameterization can enhance the weather forecast quality in cities and their surroundings. Secondly, more research is needed on how cities interact with the synoptic scale. Mahmood et al. (2014) emphasizes the importance of studying meso- and synoptic-scale interactions between urban areas and the climate system, which requires a proper urban representation in models. Thirdly, bridging the gap between weather prediction and microscale models is key for developing global digital twin models, as e.g., by ECMWF (ECMWF 2024). As these models operate on a global scale, it is crucial to determine the resolution at which urban processes can still be realistically represented. Lastly, global simulations including urban parameterization are essential for providing boundary conditions for higher-resolution regional models. The success of such regional models depends largely on the quality of the boundary conditions of the underlying model.

In this study, we investigate the applicability of the urban slab model TERRA_URB, to the global ICON-NWP of DWD at 13 km horizontal resolution. McNorton et al. (2021) suggested that incorporating an urban parameterization in the hydrostatic IFS model is only beneficial for horizontal grid resolutions finer than 9 km. Additionally, Schlünzen et al. (2023) states that resolutions of around 12 km are considered too coarse to depict urban phenomena accurately. On the other hand, Langendijk et al. (2019) shows that slab models can represent urban-rural contrasts at a 12 km resolution. This work aims to revise these statements by applying TERRA_URB to the global ICON-NWP and to evaluate whether it can effectively represent urban phenomena such as the UHI at a resolution of 13 km. To investigate the potential of TERRA_URB, the global operational ICON-NWP was used to simulate two five-day periods: one in July 2021 and another in June 2022, followed by respective runs with TERRA_URB activated. To assess the uncertainty, a 20-member ensemble was created for each simulation period.

To achieve the above-mentioned objectives, the following research questions are proposed for this work:

1. How does the inclusion of a slab model urban parameterization (TERRA_URB) in the global operational ICON-NWP influence forecast outcomes?
2. Under which weather conditions does the model output show the largest differences due to urban effects, particularly when the synoptic conditions favor the development of an UHI?

Following the motivation and overview of current research in Section 1, Section 2 summarizes the technical setup of the simulations, including the selection of the simulation periods and the key post-processing steps. Section 3 presents the simulation output with a focus on selected European cities, while Section 4 expands the analysis to a global comparison of urban areas. In Section 5, simulation results for Berlin are evaluated against observations from the urban climate station at Berlin Alexanderplatz. Section 6 discusses the findings of the study in the context of the working hypothesis. Finally, the conclusions are presented in Section 7.

2 Data and methods

To investigate the potential of TERRA_URB, two five-day periods were simulated using the global non-hydrostatic ICON-NWP, followed by a respective run with TERRA_URB implemented. To assess uncertainty, a 20-member ensemble was generated for each deterministic simulation (Zängl et al. 2015).

2.1 ICON model setup

The global ICON-NWP uses a triangular grid with a horizontal grid spacing of 13 km (ICON Model 2024). External parameters, such as topography, land-sea mask, soil type, and atmospheric aerosols, are considered constant over time and generated by the ExtPar (External Parameters) software (Asensio et al. 2020). The land cover scheme used is GlobCover2009-v5, which is currently applied operationally at DWD. To adapt the atmospheric forcing to the land use, the model employs a tile approach. Patches of the same soil type are regrouped into homogeneous classes (tiles). The surface energy balance and soil physics calculations are performed separately for each tile and then averaged over each grid cell. Since radiation is a computationally expensive physical process in the model, the grid size of the radiation scheme is reduced to 26 km (Prill et al. 2023). For the simulations including the TERRA_URB parameterization, the different grid resolutions imply that heat capacity, heat conductivity, aerodynamic roughness length, run-off, and water storage are calculated on the tiles of the 13 km grid, while bulk albedo and bulk emissivity, which depend on radiation input variables, are modeled on the tiles of the 26 km grid. TERRA_URB is widely used in various studies, with parameter values derived from the COSMO consortium's CITTA priority project (COSMO Consortium 2025). Among all urban canopy parameters, the Impervious Surface Area (ISA) is one of the most important parameters for TERRA_URB, as it defines the sealed fraction, that is, the part of a model grid cell where TERRA_URB is applied. In ICON, ISA is set to 1 for all grid cells classified as urban in the land-use dataset, and to 0 for all other classes (Campanale et al. 2025). Further details on the urban environment parameters can be found in (Garbero et al. 2021). In the current global operational set-up, TERRA_URB is not activated, meaning that urban areas are solely represented as a separate land-use type, with adjustments to the roughness length, maximum plant cover fraction, maximum leaf area index, minimum stomatal resistance, skin conductivity, snow albedo, and the maximum root depth for each land-cover class.

In addition to the deterministic runs, ensemble runs with 20 members are generated for each forecast episode. Each ensemble member involves perturbations in the initial conditions coming from the data assimilation, and the operational parameters' perturbations approach, resulting in a range of distinct predictions due to the propagation of uncertainties (Reinert et al. 2020). The ensemble simulations are based on a horizontal grid spacing of 40 km. As the main purpose of the ensemble is to assess the uncertainty of the deterministic run, this resolution is considered a reasonable compromise between computational cost and scientific outcome.

In the deterministic simulations, urban areas are identified using the tile-based approach. An entire grid is classified as urban if more than 60% of the grid cell is classified as urban land use (Asensio et al. 2020). McNorton et al. (2021) analyzed eight European cities, three (Berlin, London, and Paris) with an urban fraction of 80% and five with 50%. To make our results more comparable, we adopt a similar approach and define a 60% threshold, which accounts for the difference in grid spacing (9 km vs. 13 km). Following this classification criterion, 247 grid boxes are identified as urban areas in the deterministic run for the global domain. Each grid cell center classified as urban in the deterministic run is mapped to its nearest neighbour on the ensemble grid, which is then classified as urban.

Three focus regions are selected for this study. Berlin is the only german city that fulfills the defined urban criteria (>60% urban land) and for which hourly measurement data is available (DWD 2024). Furthermore, two other European cities are selected for analysis, Paris and Warsaw. Most existing publications on the implementation of TERRA_URB focus on Europe, facilitating the comparison with the literature (Trusilova et al. 2016; Wouters et al. 2016; Garbero et al. 2021; McNorton et al. 2021). The Urbisphere measurement campaign has selected Paris and Berlin as focus cities (Urbisphere 2024). Warsaw has been selected as the third city due to its location further east in Europe and its flat terrain, which helps minimize potential interference from local circulations. In the following, the operational run is abbreviated by OPR, and the run with TERRA_URB activated is abbreviated by URB. The years are selected based on the synoptic conditions in Europe, especially for Berlin. All simulations are conducted as free runs, which means that the model is only initialized at the start of the forecast period, with no additional data assimilation during the simulation. Hourly output was generated from 04.07.2021 at 21:00 UTC until 09.07.2021 at 21:00 UTC and from 15.06.2022 at 00:00 UTC until 19.06.2022 at 00:00 UTC. Given the expected variations in C-UHI intensities throughout the day, the simulation output is partitioned into distinct datasets for day- and nighttime, defined by the local times of sunrise and sunset at each grid cell.

2.2 Selected cases

From July 4th to July 9th, 2021, the general weather situation in central Europe was dominated by cyclonic activity over the North Atlantic with strong pressure gradients and southwesterly winds. A low-pressure system centered over the British Isles influenced the weather in central Europe and Germany during that period (Fig. 1a). Precipitation events were recorded on 4 out of 5 days, and the total cloud cover averaged to 6/8, indicating relatively high cloudiness (DWD 2024). Moist soil and an overcast sky reduced longwave radiation loss, especially in rural areas. Therefore, the C-UHI magnitude between Berlin and the surrounding rural area is expected to be small for the simulation period in July 2021. In contrast, the period of June 2022 was characterized by anticyclonic conditions, weak pressure gradients and thus only moderate advection. On June 15th, 2022, the high-pressure system over the British Isles moved towards southeastern Europe in the following days (Fig. 1b). Upstream of a low pressure system at the Iberian coast, hot air from north Africa flowed into Germany from June 18th to 19th, 2022, leading to a heatwave during this period. During the simulation period, 60 out of 362 DWD measuring stations reported new heat records for June, particularly in eastern Germany. The high temperatures and low precipitation resulted in dry soil conditions (Mahmood et al. 2022). In Berlin, no precipitation events were recorded during the simulation period, and the total cloud cover averaged to 4/8, thus lower than during the simulation period in July 2021. The heatwave primarily affected the Iberian Peninsula, Germany, and western Poland. The heat only moved east after the simulation period, affecting Warsaw (Imbery et al. 2022). The mid-June 2022 simulation period is selected because of its favourable synoptic conditions for developing a strong C-UHI, especially over Berlin.

3 Comparison of simulations for European cities

First, a comparison is made between the deterministic and ensemble simulation outputs for the focus cities identified in Section 2 (Berlin, Paris, Warsaw). As Paris extends over four ICON grid cells, the results show an average over all cells. For both episodes in 2021 and 2022, the URB run consistently yields higher 2 m temperatures during nighttime compared to the OPR run (positive values in Fig. 2a). This feature holds for both the deterministic and ensemble outputs. The day- and nighttime 2 m temperature difference between the URB and OPR runs in Berlin and Paris, are more pronounced in the 2022 case compared to the 2021 case. In Warsaw, larger differences are observed in 2021.

For the 2022 case, the deterministic simulations at 13 km grid spacing yield greater differences between URB and OPR than the ensemble median at 40 km grid spacing, both during daytime and nighttime. For the 2021 case, the ensemble simulations exhibit larger differences than the deterministic simulations in Paris for both day- and nighttime, in Berlin during the daytime, and in Warsaw at night. The results of the difference between the deterministic and ensemble runs are overall smaller during day than during night (Fig. 2b).

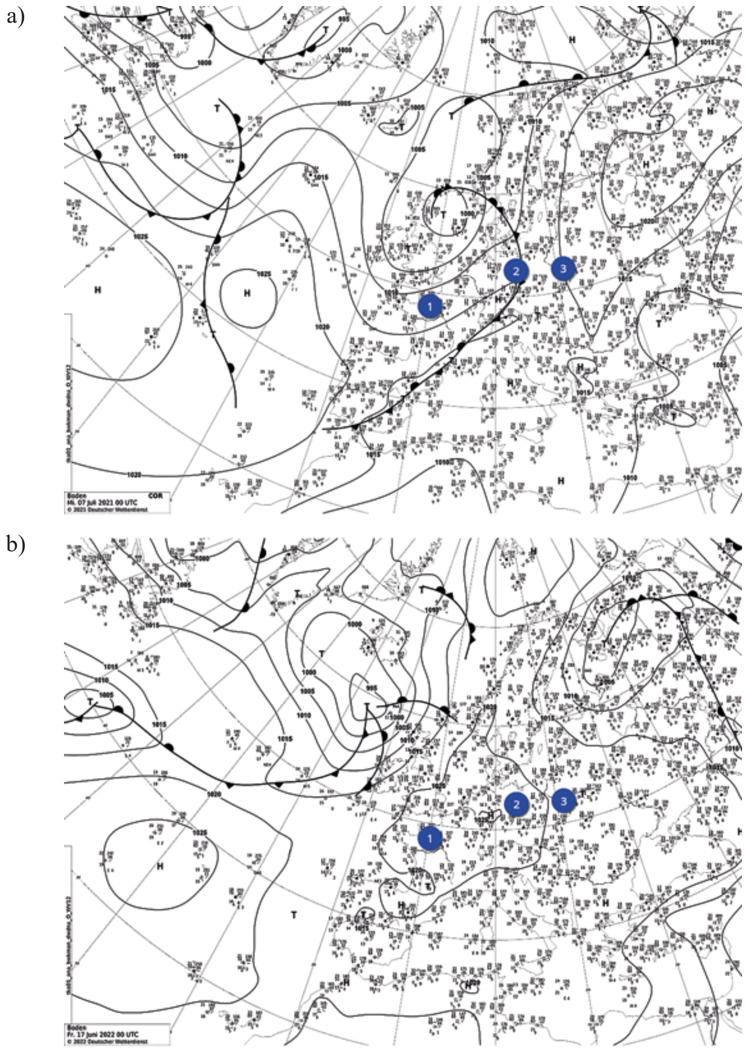

Fig. 1. Surface pressure analysis retrieved from DWD archive for 07.07.2021 00 UTC (a) and 17.06.2022 00 UTC (b) (wetter3 2024). The locations of Paris (1), Berlin (2), and Warsaw (3) are highlighted in turquoise.

Nevertheless, the medians and inter-quartile range (IQR) of all box plots are greater or equal zero. This means that the URB run produces, on average, higher mean 2 m temperatures than the OPR run, even during the day. As stated in Section 2 Warsaw was less influenced by the low-pressure systems than Berlin and Paris in July 2021 (Fig. 1a). According to DWD, Warsaw was not as severely affected by the heat in June 2022 as Berlin and Paris (Fig. 1b). Consequently, the differences in the deterministic runs for Warsaw are smaller than in Berlin and Paris, highlighting more similar synoptic conditions in both periods in Warsaw than in Berlin and Paris. Given the assumption that urban effects are less pronounced at a 40 km grid resolution compared to a 13 km grid, a smaller difference between URB and OPR is expected in the ensemble simulations relative to the deterministic run. However, as outlined, four cases in 2021 (Paris: day- and nighttime, Berlin: daytime, Warsaw: nighttime) exhibit larger differences at the 40 km resolution than at 13 km. This suggests that an urban effect is present even at a 40 km horizontal grid spacing.

4 Comparison of simulations for global urban areas

We now expand the analysis to a global perspective and consider the differences for all the 247 identified urban grid cells. The mean nocturnal 2 m temperature differences between URB-OPR for all urban grid cells are shown in Fig. 3a for 2021 and in Fig. 3b for 2022. A regional focus on Europe is provided in Fig. 4, showing the corresponding differences during a heatwave.

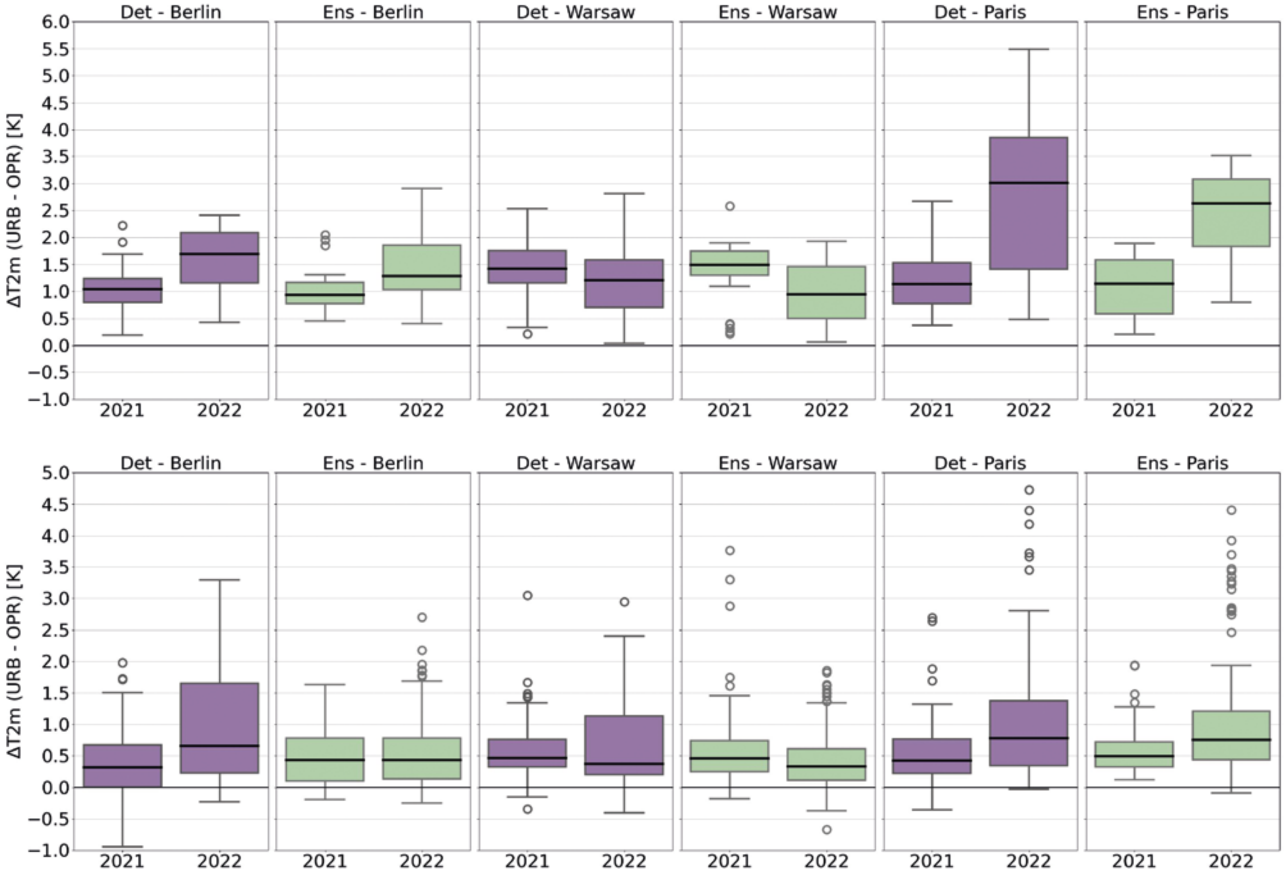

Fig. 2. Differences in hourly night- (a) and daytime (b) 2 m temperatures (URB-OPR) between deterministic simulation (13 km, purple) and 20-member ensemble mean (40 km, green) for selected Central European cities, covering the periods June 15–19, 2022, and July 4–9, 2021. The boxes present the IQR, the thick black line the median. Whiskers denote the 0.05 and 0.95-quartile range, outliers are marked as circles. Paris's data combines four ICON grid cells.

In both years, all 247 urban grid cells exhibit higher average nocturnal 2 m temperatures in the URB run compared to the OPR run (Fig. 3). In 2021, 42 urban grid cells exhibit a nocturnal 2 m temperature difference greater than 2 K, and 12 urban grid cells exceed 3 K, with the largest value of 3.9 K found in Tehran, Iran. In 2022, 45 urban grid cells exceed 2 K, 7 urban grid cells exceed 3 K, and one city surpasses 4 K. The highest URB–OPR difference in 2022 (4.2 K) is found in La Paz, Bolivia, located at an elevation of approximately 3650 m. In July 2022, a severe heatwave affected western Europe during the simulation period. As shown in Fig. 4, the URB–OPR difference in western Europe is more pronounced in 2022 than in 2021. In contrast, only minor differences are seen in eastern European urban grid cells, which were only weakly affected by the heat wave conditions in 2022. Heatwave conditions are particularly conducive to the development of a strong UHI, which explains the larger impact of the TERRA_URB implementation under such synoptical conditions.

5 Case study Berlin

5.1 Boundary layer dynamics

Our analysis now focuses on the Berlin area and in particular on the vertical temperature distribution over Berlin for the simulation period in June 2022. The difference between OPR and URB is greater in June 2022 than in July 2021, making the June 2022 analysis more illustrative and thus chosen for detailed discussion. Fig. 5 shows a zonal cross-section with vertical level temperature anomalies ($T - T$) at each height level up to 500 m. Both models depict elevated temperatures over Berlin. Directly above the city center, the URB run exhibits higher temperatures than the OPR run. In both runs, the temperatures gradually decrease as moving outward from the city. The relatively higher temperatures above the city extend to an altitude of around 200 m. The higher temperatures in both simulations extend to the west, covering the adjacent rural area, a phenomenon described as "urban plume" in Oke et al. (2017). In the URB run, the temperature a)

b)

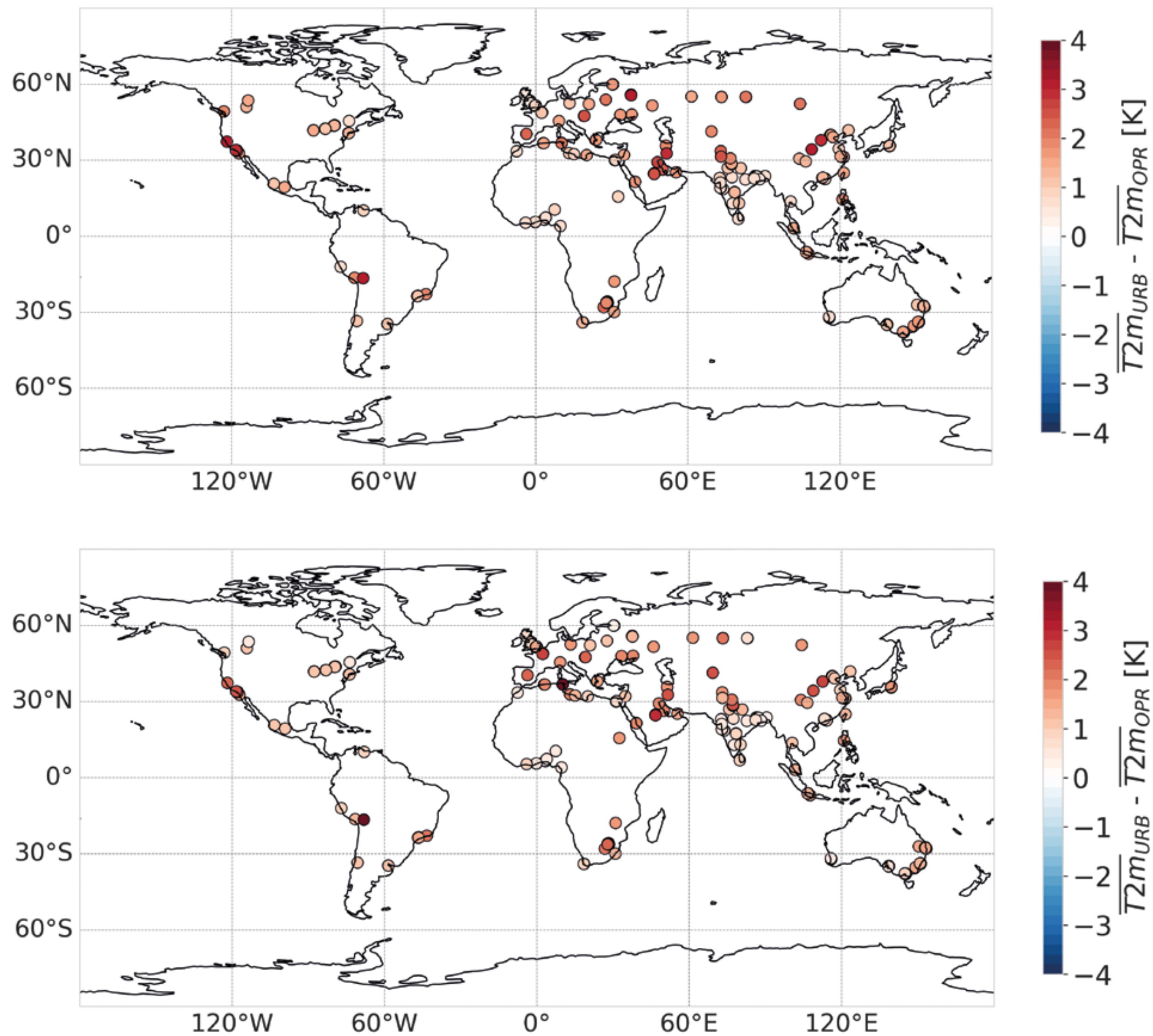

Fig. 3. Difference between nocturnal mean 2 m temperature [K] (URB-OPR) for all 247 identified cities from 04.07.2021 21:00 UTC to 09.07.2021 21:00 UTC (a), 15.06.2022 00:00 UTC to 19.06.2022 00:00 UTC (b).

anomalies extend further, around 90 km, to the west than in the OPR run. The surrounding rural region is selectively colder in URB than in OPR near the surface, for example, at the small hill at 13.78° longitude.

5.2 Verification with urban climate station observations at Alexanderplatz, Berlin

Verifying the NWP model output within cities is generally challenging due to the limited number of official urban climate stations worldwide. We have chosen Berlin as an example for verification, not only because the city is classified as urban (>0.6 urban land use), but also because of the data availability of an official urban climate station at Berlin Alexanderplatz. In June 2022, the difference between the predicted OPR and the observations (OBS) resulted in an RMSE of 4.2, while the corresponding RMSE for URB is 3.1 (Table 1). This indicates that the implementation of TERRA_URB enhanced the forecast accuracy by 26% for a 5-day lead time. Shorter lead-times show a better RMSE improvement, reaching 28% for a 4-day lead time and 45% for a 3-day lead time. Regarding the 2021 case, the RMSE values for OPR and URB against the observational data (Table 1) are 1.9 and 1.4, respectively, reflecting a generally more accurate forecast for the period. The RMSE improvement of URB compared to OPR was more modest, around 26% for a 5-day lead time. Similarly, reducing the lead time led to RMSE improvements of 21% for days 1–4 and 26% for days 1–3. For June 2022, the daily course of the air temperature is well reflected, and the daily minimum and maximum values of both runs follow that of

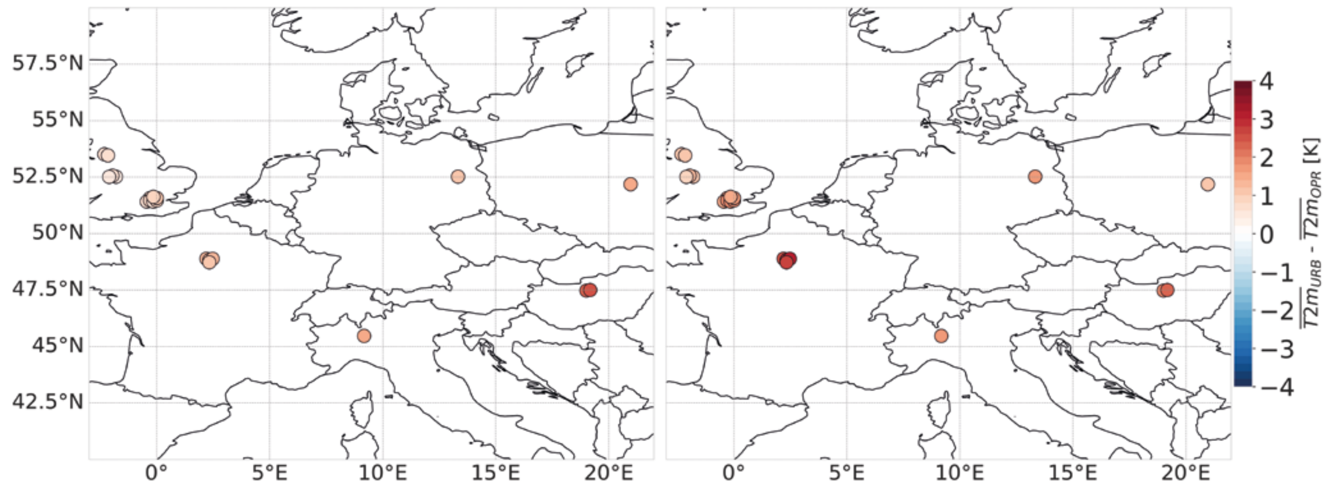

Fig. 4. Difference between nocturnal mean 2 m temperature [K] (URB-OPR) for central European cities from (a) 04.07.2021 21:00 UTC to 09.07.2021 21:00 UTC, and (b) from 15.06.2022 00:00 UTC to 19.06.2022 00:00 UTC.

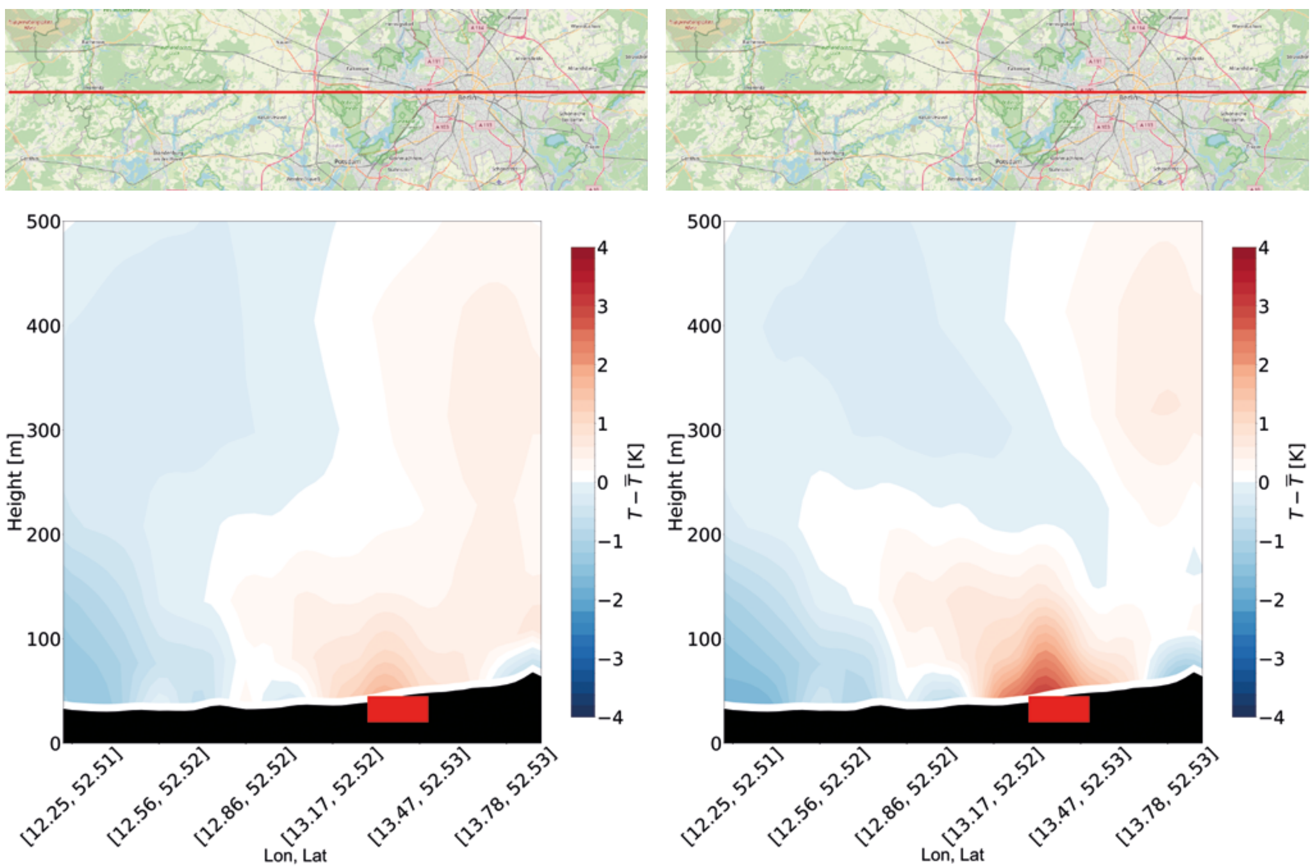

Fig. 5. Zonal cross-section plot of $T - \overline{T}$ [K] versus height [m] (altitude up to 500 m) for Berlin on 16.06.2022 00:00 UTC. Left: Cross-section location (top) and OPR cross-section (bottom). Right: URB cross-section. Wind direction is indicated by the arrows. The red rectangle is the location of the Berlin grid cell.

the OBS (Fig. 6). The observational data is mostly within the URB ensemble spread. Slight deviations, where the OBS is neither in the URB nor OPR ensemble spread, exist during nights from 14.06.22 to 15.06.22, from 16.06.22 to 17.06.22, from 17.06.22 to 18.06.22, and for short periods at noon on 16.06.22 and 17.06.2022. The difference between OBS and

Table 1. RMSE values for OPR and URB compared to observations, along with the percentage improvement in RMSE including TERRA_URB, for the deterministic simulation outputs at different lead times for July 2021 and June 2022.

July 2021				
	Lead time [Day]	**RMSE OPR**	**RMSE URB**	**RMSE improvement [%]**
	1–5	1.9	1.4	26
	1–4	1.4	1.1	21
	1–3	1.5	1.1	26
June 2022				
	Lead time [Day]	**RMSE OPR**	**RMSE URB**	**RMSE improvement [%]**
	1–5	4.2	3.1	26
	1–4	2.8	2.0	28
	1–3	2.0	1.1	45

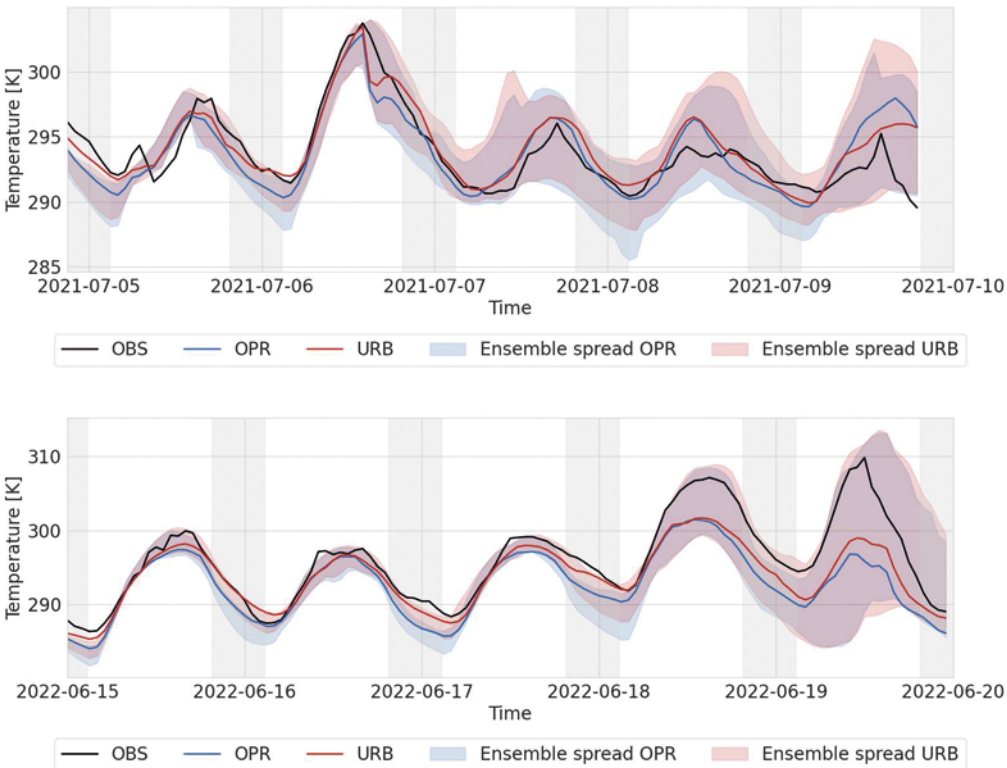

Fig. 6. Deterministic and 20-member ensemble 2 m temperature [K] simulation results from (a) 04.07.2021 21:00 UTC to 09.07.2021 21:00 UTC and (b) 15.06.2022 00:00 UTC to 19.06.2022 00:00 UTC. Urban climate station 2 m temperature [K] measurements for Alexanderplatz, Berlin, are highlighted in black (DWD 2024). Nights, defined as the time between sunset and sunrise, are shaded in grey.

the deterministic runs increases with increasing lead time. Overall, URB and OPR both underestimated the nighttime air temperature in June 2022 except for the night of 15 to 16.07.2022. However, it is noticeable that URB predicts better nighttime 2 m temperatures than OPR. The increase in air temperature in the morning is depicted comparatively well by the models, but the daily maximum values are underestimated. The comparison for July 2021 shows more heterogeneous results: On the first day, the daily maximum of the temperature at Alexanderplatz is measured later than that of both model runs. This temporal shift can no longer be seen in the following three days. Over the further time series, no period can be identified in which an over- or underestimation of both model runs can be recognized over several consecutive hours. From the night of 04.07.21 to 05.07.21 and up to the daily maximum on 05.07.21, the measurement data from Alexanderplatz fall outside both ensemble spreads. However, except for the last 5 hours, the rest of the time series shows the observations within the URB ensemble spread. The improved RMSE values for both simulation periods, and the enhanced prediction of nighttime 2 m temperatures in June 2022, highlight the added value of incorporating urban parameterization in ICON.

6 Discussion

Following the presentation of the results, We now discuss them in relation to the theory of urban climatology and previous studies, focusing on the three cities Paris, Berlin, and Warsaw. The deterministic and ensemble simulations by the URB runs reveal higher 2 m nighttime temperatures in comparison to the OPR runs for both considered periods. On average, the URB runs also produced higher 2 m temperatures during the day, but the differences are less pronounced than those at night. From a theoretical perspective, the C-UHI effect leads to larger differences in 2 m temperatures at night compared to daytime. Thus, from a physical process-understanding perspective, the simulation results are plausible. The results of the ensemble simulation are consistent with previous findings from Katzfey et al. (2020), who showed that including an urban canopy scheme in the global Conformal Cubic Atmosphere Model (CCAM) produced an UHI signal of approximately 1 K in grid cells with at least 50% urban fraction at a coarser 50 km resolution. In this context, the C-UHI signal identified in our 40 km ICON-NWP ensemble supports the plausibility of these earlier findings actually on a global scale.

Using Berlin as a case study, the simulation period in June 2022 represents weather conditions conducive to a strong C-UHI, while the period in July 2021 reflects conditions less favorable for a well-developed C-UHI. The results show that the forecast for the Berlin Alexanderplatz station has higher RMSE values in June 2022 (OPR: 4.2, URB: 3.1, for a 5-day lead time) than in July 2021 (OPR: 1.9, URB: 1.4, for a 5-day lead time). In both periods, integrating the slab model TERRA_URB improved the 2 m temperature forecast compared to the urban station data. Trusilova et al. (2016) reported that for Berlin different urban parameterization schemes resulted in RMSE values between 1.52 and 1.70 over the entire year of 2002 compared to observational data, including their simulation with TERRA_URB. Implementing a Single-Column Urban Canopy scheme within the ECMWF's IFS model at a global resolution of 9 km, McNorton et al. (2021) observed a decrease in the RMSE from 1.28 to 1.11 over July 2012 for Berlin. During the 5-day simulation period in June 2022, the RMSE values of the 2 m temperature are higher than those reported by McNorton et al. (2021) and Trusilova et al. (2016). The discrepancy with Trusilova et al. (2016) may be attributed to the difference in grid resolution (1 km versus 13 km), while the difference with McNorton et al. (2021) could be due to the shorter simulation period (5 days vs 1 month). In addition, differences in the simulation setup likely play a role: Trusilova et al. (2016) employ a nested configuration over Berlin that is driven by ERA-5 in the outermost domain, whereas McNorton et al. (2021) use an offline modeling approach with regularly updated atmospheric boundary conditions from ERA-5, in contrast to the free-running simulations presented here. The RMSE values for 2021 are generally much lower and more closely aligned with the literature compared to the 2022 results. We hypothesize that a mesoscale urban effect primarily manifests on clear, cloud-free days and nights. The results show a larger model-observation discrepancy under such weather conditions compared to overcast days. The activation of TERRA_URB partially mitigates this disparity. Consideration of zonal cross-sections of temperature level-wise anomalies revealed that the land-surface atmosphere component TERRA, already employed in the operational weather forecast within ICON, does represent the UHI. TERRA classifies urban areas as distinct soil types and adjusts the roughness length and vegetation parameters accordingly. This could explain the higher temperatures observed near the city in the OPR run. However, under the prevailing synoptic conditions, one would expect higher temperature differences between Berlin and its surrounding areas. The simulation with TERRA_URB displayed stronger temperature anomalies, interpreted as more realistic and aligned with the expected temperature differences. In addition to the different synoptic conditions, variations in urban land-use fractions and the resulting ISA values may also contribute to the differences. All urban grid cells in our study have more than 60% urban land-use, but further clustering them by their exact urban fraction could help explore whether TERRA_URB behaves differently in areas with varying urban densities. Two primary results can be drawn from this case study. First, the global ICON model inadequately captures urban weather, especially under certain synoptic conditions that favour the development of a strong C-UHI. Second, while incorporating a slab urban parameterization scheme improves forecasting, there is still room for improvement. It should be noted that the Alexanderplatz urban climate station is not representative of the entire 13 km grid cell. In less densely populated areas, the underestimation of the 2 m temperature would have been smaller. Nevertheless, many people live in such densely constructed areas, and these areas are at risk when planning heat protection concepts.

7 Conclusions

In this study, We investigated whether a global grid resolution of 13 km in the ICON-NWP model is sufficient to represent the C-UHI phenomenon. Two distinct periods (July 2021, June 2022) characterized by different large-scale weather conditions over Germany were selected for this study. In both cases, two free simulation runs were conducted for a 5-day period: one using the slab model TERRA_URB (URB) and one without it (OPR). To address the uncertainty of the forecast, an additional 20-member ensemble was incorporated for each period and setup. Based on the results, We draw the following conclusions regarding the influence of a slab model urban parametrization in the global operational ICON-NWP and the weather conditions under which urban effects become most apparent. First, the comparison between simulations with (URB) and without (OPR) the TERRA_URB scheme demonstrates that including the slab model urban parametrization leads globally to increased 2 m air temperatures, especially during nighttime. These differences are generally classified as improvements, as indicated by reduced RMSE values when compared to observational data from the urban climate station at Alexanderplatz in Berlin. Second, with respect to the weather conditions under which urban effects are most prominent, this study provides an initial assessment rather than a definitive conclusion. The two analyzed simulation periods represent contrasting synoptic conditions. Results indicate that urban effects are more pronounced under clear-sky, calm conditions, which are favorable for a well-developed C-UHI. In such cases, the model-observation discrepancy is larger, and the inclusion of TERRA_URB leads to a partial reduction of this gap. However, due to the limited number of cases analyzed, this conclusion remains preliminary. A more comprehensive evaluation, including additional simulation periods and further observational data from Berlin or other urban stations, would be necessary.

Data availability statement: The simulation output (deterministic + ensemble) for the 247 selected urban areas can be requested from the author. The urban climate station data is provided by the Deutscher Wetterdienst (DWD) and is openly accessible through their website.

Author contributions: MB, AV and LE conceived and designed the study. MB performed the ICON simulations with the help of AV, performed the data analysis and prepared the figures. MB wrote the initial paper draft. All authors discussed the results and contributed with manuscript revisions.

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