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High Resolution WRF Modelling of Extreme Heat Events and Mapping of the Urban Heat Island Characteristics in Athens, Greece

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Abstract: In recent decades, large-scale urbanisation has developed rapidly, resulting in significant changes in the local and regional environment and climate. Large metropolitan areas worldwide induce significant changes in local atmospheric circulation and boundary layer meteorology by modifying the underlying surface characteristics and through the emission of anthropogenic heat and pollutants into the atmosphere. We investigate the urban heat island (UHI) characteristics in the city of Athens, Greece, which is one of Europe's largest metropolitan complexes with a population of approximately 3.7 million inhabitants. The UHI effect is intense due to the city's size, dense construction, high incident solar radiation, and almost complete lack of natural vegetation, with previous studies suggesting a temperature rise of 4 °C on average in the city centre compared to summer background conditions. We used high-resolution WRF simulations (1-km horizontal grid) driven with ERA5 reanalysis data to produce surface temperature maps in the city of Athens and the surrounding areas (Region of Attiki) during the summer period of 1 July–20 August 2021. Different model parameterizations were tested, both with respect to urban characteristics and physical parameters. The daily minimum and maximum temperatures ($T_{\min}$ and $T_{\max}$) derived from the model were validated against observational data from a dense network of weather stations covering metropolitan Athens and surrounding locations. We further investigate the influence of different meteorological conditions on the UHI gradients as produced by the model and the observational dataset, including the extreme heat wave of 28 July–5 August 2021, during which persistent maximum temperatures of >40 °C were recorded for nine consecutive days. The results indicate a strong correlation between WRF output and recorded minimum and maximum temperatures throughout the test period (R ranges from 0.80 to 0.93), with an average mean absolute bias (MAB) of 1.5 °C, and reveal the intensity and spatiotemporal variability of the UHI phenomenon in the city of Athens, with UHI magnitude reaching 8–9 °C at times. Our work aims to maximise the potential of using high-resolution WRF modelling for simulating extreme heat events and mapping the UHI effect in large metropolitan complexes.

Keywords: urban heat island; WRF; high-resolution climate models; urban climate; climate change



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1. Introduction

In recent decades, large-scale urbanisation has developed rapidly, resulting in significant changes in the local and regional environment and climate. Large metropolitan areas worldwide induce significant changes in local atmospheric circulation and boundary layer meteorology by modifying the underlying surface characteristics and through the emission of anthropogenic heat and pollutants into the atmosphere [1,2]. An urban heat island (UHI) is a metropolitan area that is significantly warmer than its surroundings, with a number of studies suggesting that cities can have ambient air temperatures up to 10 °C warmer than

their surroundings [3,4]. Heat islands form as vegetation is replaced by asphalt, concrete, and other building materials for roads, buildings, and other structures that form an urban landscape. These surfaces have different physical and thermal properties, which means that they absorb solar radiation instead of reflecting it, causing the surface and ambient air temperature to rise, creating a “microclimate” [5–7]. Other contributing factors to the UHI effect include:

- Size and shape of urban structures: Aerodynamically, cities have different characteristics than the surrounding land cover. Tall buildings form a barrier, reducing surface wind speeds, while urban canyons formed by rows of buildings trap heat inside them [8,9].
- Urban deserts: Large city complexes have little vegetation and are constructed with materials that are impermeable to rain. This combination leads to a lack of evapotranspiration, which increases sensible heat [10,11].
- Anthropogenic emissions: The release of heat from activities such as air conditioning and the combustion of fossil fuels can also raise urban temperatures [12–14]. Recent studies indicate that atmospheric pollution (e.g., aerosols) is also a contributing factor to UHIs through reducing radiative cooling, and its effect on nighttime temperature is more pronounced [15].

The UHI is a well-documented phenomenon in the city of Athens, Greece [16–20], with studies suggesting a temperature rise of 4 °C on average in the city centre compared to summer background conditions. The UHI effect is intense due to the city’s size, the dense way that it is constructed, high incident solar radiation, and the almost complete lack of natural vegetation. Athens has been experiencing increased warming during the last decades, which in the summer amounts to approximately +1 °C/decade since the mid-1970s, attributable to both global warming and growing urbanisation [15,21]. Heat waves are nowadays common during the summer months, with temperatures reaching or exceeding 40 °C, which strongly increases the thermal risk and vulnerability for urban residents. In an early study [22], it was estimated from air temperature data that the UHI intensity in Athens was up to 3 °C during the period 1961–1982. In a later study [16], hourly ambient air temperatures recorded at twenty-three stations in and around the Athens region were analysed, demonstrating that the heat island intensity follows periodic and nonperiodic fluctuations, depending on weather conditions, topographic, and topoclimatic complexities and synoptic flow patterns. The mean seasonal values of the UHI in Athens were estimated at 5.4 °C in the summer, 3.2 °C in the autumn, 2.1 °C in the winter, and 3.1 °C in the spring. These findings were recently confirmed [20], as daily air temperature differences between the warmest and the coolest zones of the city centre were estimated from 5 °C up to 8 °C, a variation strongly dependent on meteorological conditions. The link between heat waves and UHI in Athens has also been investigated [23]. A positive feedback relationship between UHI and heat waves was reported, with an intensification of the average UHI magnitude by up to 3.5 °C during heat waves compared to summer background conditions. Studies in a number of other cities have also looked into how UHI responds to extreme heat conditions. Generally speaking, simulated UHI values during a heat wave tend to increase in comparison to preheat wave conditions, mainly due to the lower moisture and reduced wind speed in urban areas during the heat wave [24]. Also, UHI intensity observed at night was significantly higher, validating its typical nocturnal predominance [25,26]. Coastal areas with predominant sea-breeze circulation showed larger daytime UHI responses to heat waves. The contrasting patterns observed during sea breezes and land breezes could possibly explain these differences [27].

The UHI characteristics are city-specific, and temperature gradients across a large metropolitan area depend on a number of factors, including urban form, urban function, location, and regional climate [15]. The UHI effect can have a strong negative impact on local climate characteristics, particularly during the summer period, by increasing maximum daytime and nighttime temperatures, which in turn leads to higher energy demand for cooling [3,28], higher illness/mortality rates associated with heat stress [29,30],

and more frequent air pollution incidents [31]. The increased frequency of heat wave occurrences in urban environments can have significant negative impacts on the local environment, the economy, and public health. Furthermore, diurnal UHI intensities increase with higher absolute temperatures, creating a positive feedback relationship between heat waves and UHIs associated with an increased thermal risk and vulnerability of urban populations [19,23]. The UHI effect is expected to be more intense in urban centres across the Mediterranean region, as future increased temperature rates due to global warming are projected to exceed global rates by 25%, with summer warming being 40% larger than the global mean over the long term [15]. As extreme heat events in the region become more frequent and longer-lasting, the UHI effect further exacerbates their impact on urban environments. There is an urgent need for reliable urban temperature projections that can be used for developing city-specific UHI mitigation and adaptation measures.

The present study aims to provide additional information about the UHI effect in the GAA, by analysing data from a dense network of weather stations located in different urban and periurban surroundings and, at the same time, employing the state-of-the-art Weather Research and Forecasting (WRF) model [32] configured and parameterized specifically for high-resolution urban studies. Numerical weather prediction (NWP) models are a valuable tool for assessing and forecasting urban interactions with the atmospheric environment and have been used to provide a detailed analysis of urban microclimate in many parts of the world [33–39]. Our work aims to maximise the potential of using WRF in urban simulation studies by testing several parameterization schemes to predict daily minimum and maximum temperatures and validating the results with a high-resolution gridded observational dataset. The innovative elements of our methodology in comparison with previous studies are: (a) the WRF model is downscaled at 1-km horizontal resolution, offering an analytical reconstruction of temperature gradients over the Greater Athens Metropolitan Area (GAA). At the same time, the use of high-resolution static datasets and modelling of the individual surface and activity characteristics for the city of Athens with the Urban Canopy Model ensures higher model accuracy and forecasting skill. (b) Different complex schemes are tested in order to demonstrate the optimal model configuration. The output of each scheme is validated for a period of two months with the use of in-situ data retrieved from a dense array of meteorological stations covering the study area. Thus, results are accurately and thoroughly validated throughout the study area, providing a detailed assessment of spatiotemporal variations of the UHI effect in a large metropolitan complex such as GAA, where complex topographical and meteorological characteristics need to be defined.

2. Methods and Data

2.1. Description of the Study Area and Experimental Setup

The Greater Athens Area (GAA) is a large metropolitan complex occupying 2928 km² on the Attiki Peninsula, Greece, with a population of 3.7 million (Figure 1). The urban heat island (UHI) effect is intense in the Greek capital, especially during the summer months. Low vegetation cover (less than 10%), dense construction, high insolation, anthropogenic heat fluxes, and atmospheric pollution contribute to the effect. The local topography is also a factor that plays a major role in the formation of the local microclimate. Athens is situated in the western angle of Attiki, on a coastal basin surrounded by four mountains (Hymettos, Pentelikon, Parnitha, and Aigaleo), and therefore air circulation patterns and boundary layer conditions can vary extremely, depending on synoptic orientation during warm periods of the year [40]. Previous studies suggest a 3–8 °C temperature gradient between central and periurban districts [16,20,23,36], depending on seasonal, diurnal, and weather characteristics.



Figure 1. Satellite picture of the study area, showing Attiki Peninsula and the urban extent of GAA.

In order to verify the above findings and estimate the UHI intensity in the city of Athens for a variety of atmospheric conditions, we produce high-resolution 1-km horizontal grid maps of temperature gradients over the study area by employing the WRF model configured locally for urban simulations. At high resolution, the model is expected to capture near-surface atmospheric processes that are related to the complex topography of the Attiki Peninsula, such as orographic flows, turbulent boundary layer interactions, sea breezes, etc. [41,42]. At the same time, a dense network of ground-based meteorological stations is used to provide an in-situ dataset of surface temperatures. Stations are operated by the National Observatory of Athens' METEO unit [43] and cover the whole geographic extent of the study area, with a higher concentration within the urban fabric, as shown in Figure 2b. Forty-eight stations are used, classified into four categories according to location (urban high-density, urban low-density, periurban, and coastal). Daily $T_{\max}$ and $T_{\min}$ temperatures are recorded during a period of 50 days (July–August, 2021), which includes a heat-wave event (27 July–5 August) when maximum temperatures exceeded 40°C for 10 consecutive days.

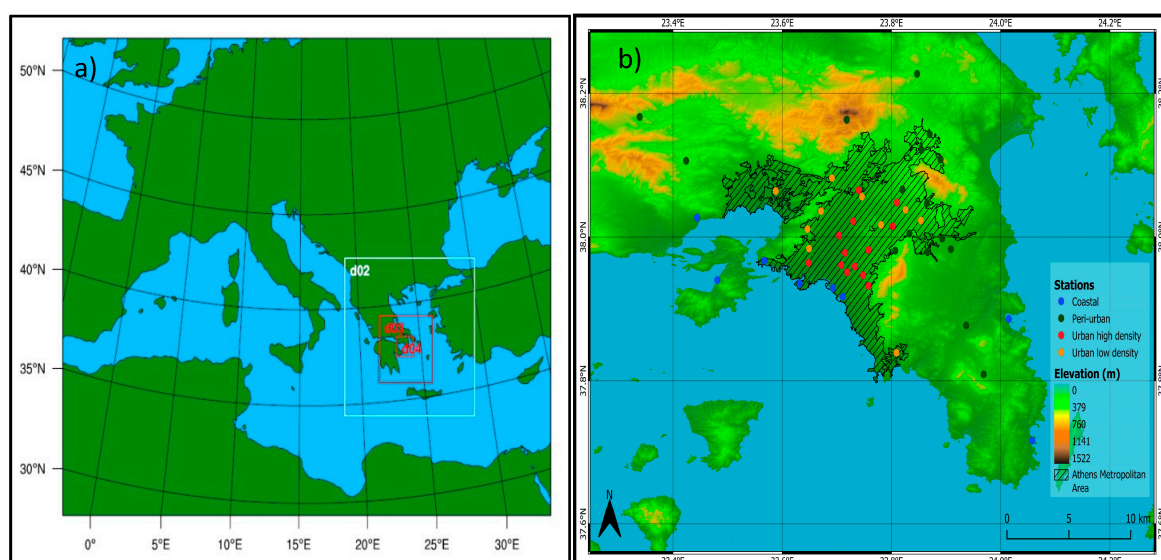


Figure 2. (a) Map showing the four nested domains (d01–d04) used for WRF weather reanalysis over Attiki Region. (b) Map of the inner domain (d04), showing the Athens metropolitan area (hashed black). The 48 ground stations of the METEO network used for the WRF validation are marked in blue (coastal), green (periurban), red (urban high-density), and yellow (urban low-density).

In-situ data are used both as a standalone method of mapping the UHI effect and for validating model output. High-resolution maps (1 km grid) are produced by applying kriging with external drift (KED) to daily $T_{\max}$ and $T_{\min}$ values, considering the elevation as a covariate to account for elevation dependencies (the station's elevation for modelling and the WRF elevation for interpolation) [44]. The gridded observational dataset provides a high-resolution visualisation of the UHI effect on a daily basis, and a tool for validating WRF output and estimating model bias.

In-situ data are also used as point observations at the 48 points where stations are located, thus providing a benchmark of observational data for WRF validation. The correlation between observed and predicted time series is established with the use of the following metrics, which provide a quantitative measure of the prediction skill of different model schemes compared to the in-situ dataset:

Mean Absolute Bias (MAB):

$$|\bar{\sigma}| = \frac{\sum(|f_i - o_i|)}{N} \quad (1)$$

Pearson Correlation Coefficient (R):

$$r = \frac{\frac{1}{N} \sum_i (f_i - \bar{f})(o_i - \bar{o})}{\sigma_f \sigma_o} \quad (2)$$

where f_i represents the model value, o_i is the observational value, N is the number of pairs in the examined time series, σ_f is the standard deviation of the model values, and σ_o is the standard deviation of the observations.

2.2. Model Configuration and Parameterization of Physical Components

Four nested domains (d01–d04), each with a horizontal resolution of 27, 9, 3, and 1 km, are employed for the high-resolution dynamical downscaling simulation carried out with WRF v 4.2.1 over the Attiki region (Figure 2a). Domains are two-way nested, which means they can provide feedback to their parent domain. There are 45 sigma levels in the vertical layer distribution up to a height of approximately 20 km (0.1 hPa), with the lowest layers being more densely inhabited. We use ERA5 global climate reanalysis initial conditions with a 0.25° horizontal resolution and a 3 h temporal resolution. ERA5 is the latest reanalysis dataset provided by ECMWF, encompassing a detailed record of global atmospheric, land surface, and ocean observations. With an hourly output and an uncertainty estimate from an ensemble (3 hourly at half the horizontal resolution), it is capable of providing an accurate representation of boundary conditions. The model is initiated every day at 18:00 local time, producing 30 h of simulations, with the first 6 h being spin-up time. Model output is recorded every hour, from which temperatures at 2 m height (T_2) are extracted, and daily maximum and minimum temperatures ($T_{\max}$ and $T_{\min}$) are calculated. Land-use categories are taken from the MODIS 500 m MCD12Q1 Land Cover Dataset, and the initial Global 30 Arc-Second Elevation Model (GTOPO30) land topography dataset is replaced with the ASTER 1" global GDEM high-resolution terrestrial dataset for the inner 1 km domain (d04), with a horizontal grid of 30 m.

Five distinct schemes are tested for the model's physical and dynamical parameterization in an effort to evaluate how well each scheme performs. A number of previous studies have validated the results of various WRF model configurations with observations made under specific conditions [42,45–47], demonstrating that globally, a single optimal scheme does not exist, but rather different schemes produce better results with respect to application, domain, season, variable, etc. The output of five distinct parameterization schemes is therefore tested against ground data from 48 permanent stations in the research region (d04) over a fifty-day period (1 July–20 August 2021) in order to evaluate the model.

With respect to physical parameterization, the schemes are selected based on existing studies where similar high-resolution WRF simulations were used [42,47–49]. All five schemes

use the same parameterization for microphysics (Single-Moment 6-Class WSM6 scheme) [50], land surface (Noah Land-Surface Model) [51], radiation physics (RRTMG for shortwave and longwave radiation) [52], and cumulus convection (Kain–Fritsch scheme) [53]. Two different surface layer/planetary boundary layer combinations are tested, as these parameters have a strong impact on the estimation of surface temperatures. In the first two schemes (MOD1), the MM5 (MM5 similarity) [54], surface layer coupled with the YSU (Yonsei University) [55], planetary boundary layer scheme is used, whereas in the next three schemes (MOD2), we test the MO (Janjic-Eta similarity) [56] and MYJ (Mellor–Yamada–Janjic) [56] pair. Table 1 lists the physical parameterization used in each scheme.

Table 1. WRF parameterization options used for the sensitivity analysis.

	MOD1URB	MOD1VEG	MOD2URB	MOD2URB_MOS	MOD2VEG
Microphysics (mp)	WSM6	WSM6	WSM6	WSM6	WSM6
Land surface (sf)	NOAH	NOAH	NOAH	NOAH	NOAH
Surface layer (sfclay)	MM5	MM5	MO	MO	MO
Radiation physics (sw)	RRTMG	RRTMG	RRTMG	RRTMG	RRTMG
Radiation physics (lw)	RRTMG	RRTMG	RRTMG	RRTMG	RRTMG
Planetary boundary layer (pbl)	YSU	YSU	MYJ	MYJ	MYJ
Cloud physics scheme (cu)	Kain-Fritsch at D1 and D2	Kain-Fritsch at D1 and D2	Kain-Fritsch at D1 and D2	Kain-Fritsch at D1 and D2	Kain-Fritsch at D1 and D2
Urban Canopy Model	On for D4	Off	On for D4	On for D4 and Mosaic LC	Off

Additionally, the effect of urban landscape modifications on model output is examined by using different configurations with respect to the urban canopy model (UCM) in the inner domain (d04). In schemes MOD1URB and MOD2URB, the Single Layer Urban Canopy Model (SLUCM) used with NOAH land surface is turned on for d04, parameterised according to the specific urban surface characteristics of the city of Athens (building block dimensions, road width, surface albedo, vegetation fraction, anthropogenic emissions, etc.). In schemes MOD1VEG and MOD2VEG, the simple NOAH land surface model is used with a modified VEGPARM table to account for specific vegetation and urban characteristics in the study area. In addition, a fifth scheme is tested (MOD2URB_MOS), where the Mosaic subtiling option is turned on in the MOD2URB scheme, which allows fractional areas of different land-use categories within a grid cell [57] in the NOAH land surface model, in order to produce a more detailed and representative landscape.

The methodology followed ensures that the WRF high-resolution urban simulation employed for studying the UHI effect and temperature gradients in the city of Athens is configured to produce results of the highest possible accuracy. By testing a variety of different parameterization schemes (combining physical and urban landscape components) for a period of fifty days and validating the output against a dense network of observations, we verify which configurations have the best performance with respect to predicting daily maximum and minimum surface temperatures.

3. Results

3.1. Sensitivity Analysis and Validation of WRF Schemes with In-Situ Data

The sensitivity analysis is performed for a fifty-day period (1 July–20 August 2021), with the aim of testing the forecasting skill of five different WRF parameterization schemes with respect to daily maximum ($T_{\max}$) and minimum ($T_{\min}$) surface temperatures. The output of each scheme (temperature at 2 m, T2) is validated against in-situ data at the nearest grid point. These are provided by a dense array of 48 urban weather stations that belong to the NOA METEO Network, as illustrated in Figure 2b. The selection of the test period for the sensitivity analysis is based on weather conditions (i.e., high temperatures and the occurrence of a heat wave during which daily maximum temperatures exceeded 40 °C for nine consecutive days). Time series of daily $T_{\max}$ and $T_{\min}$ for the five WRF schemes vs.

in-situ data at four selected stations are presented in Figures 3 and 4, respectively. Each station is representative of one of the four categories according to location (NKOS = urban high-density, KIFI = urban low-density, FALI = coastal, and MAND = peri-urban).

With respect to $T_{\max}$, results at most stations exhibit a strong correlation between WRF and in-situ values. The Pearson correlation coefficient R on average is high ($R > 0.8$) for all schemes; however, schemes with the MOD2 physical parameterization (MO Eta-Janjic surface layer coupled with MYJ boundary layer) seem to perform significantly better. Values of R are higher than 0.9 for the three MOD2 schemes overall, with MOD2VEG and MOD2URB_MOS exhibiting the stronger correlation ($R = 0.92$), as presented in Table 2. When we take into account urban stations separately, MOD2URB_MOS exhibits the strongest correlation for $T_{\max}$ ($R = 0.93$). On the other hand, schemes with the MOD1 physical parameterization (MM5 similarity surface layer coupled with YSU boundary layer) exhibit a weaker correlation, with R ranging from 0.80 to 0.82 for MOD1VEG and MOD1URB, respectively (0.82 to 0.83 for urban stations). Similarly, the mean absolute error (MAE) for $T_{\max}$ is in the order of 1.5–3 °C for all WRF schemes, with MOD2 schemes exhibiting lower bias and higher accuracy overall. The average MAE for the three MOD2 configurations for all stations is in the region of 1.5 °C, and even lower when only urban stations are considered (1.34 °C for the MOD2URB_MOS scheme). Model bias for MOD1 schemes is higher, and MAE is approximately 1 °C higher than MOD2 (in the range 2.3–2.5 °C for all stations).

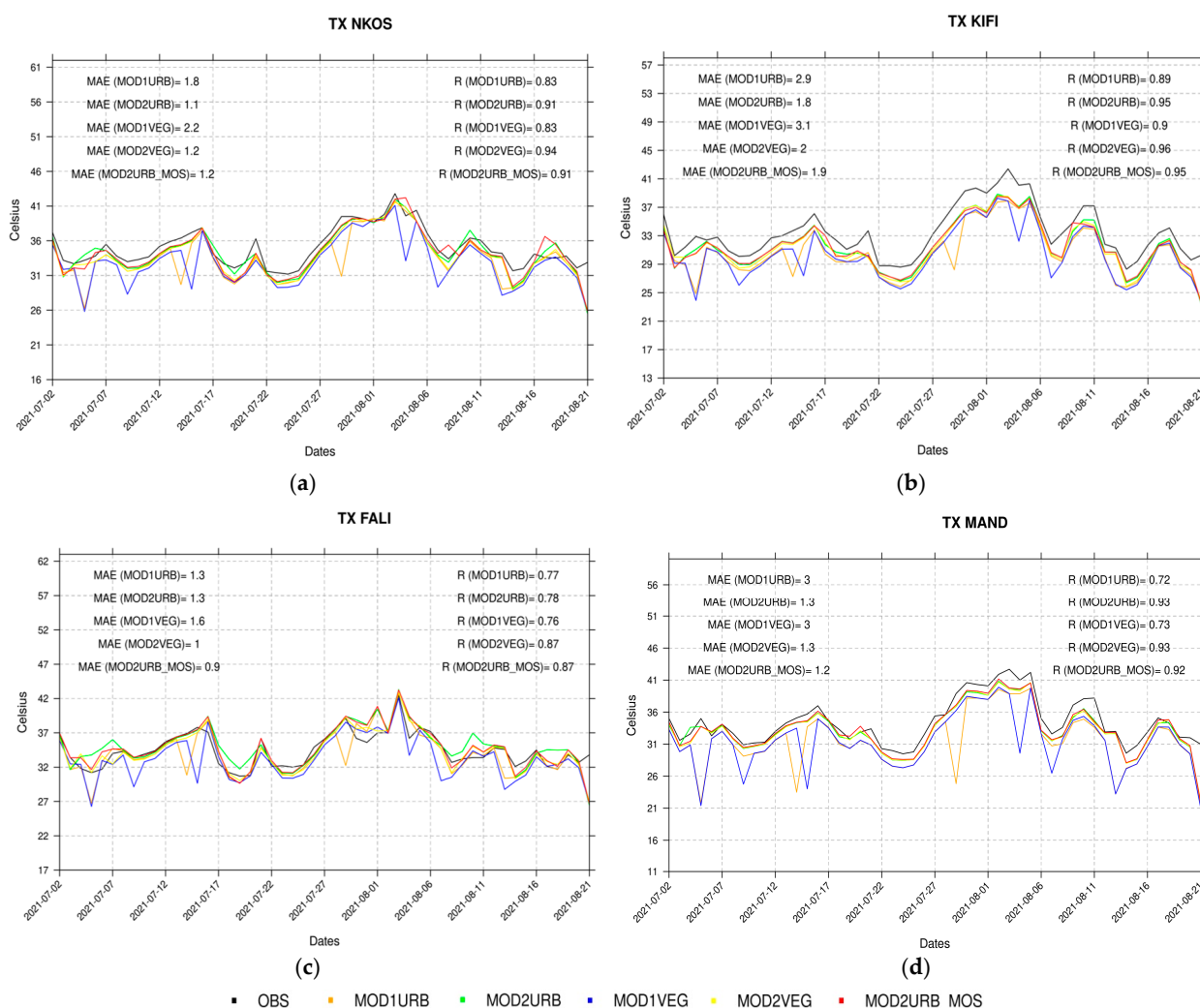


Figure 3. Observed and simulated $T_{\max}$ time series of five different WRF schemes vs. OBS at 4 METEO stations, NKOS (a), KIFI (b), FALI (c), and MAND (d) over the test period (1 July–20 August 2021).

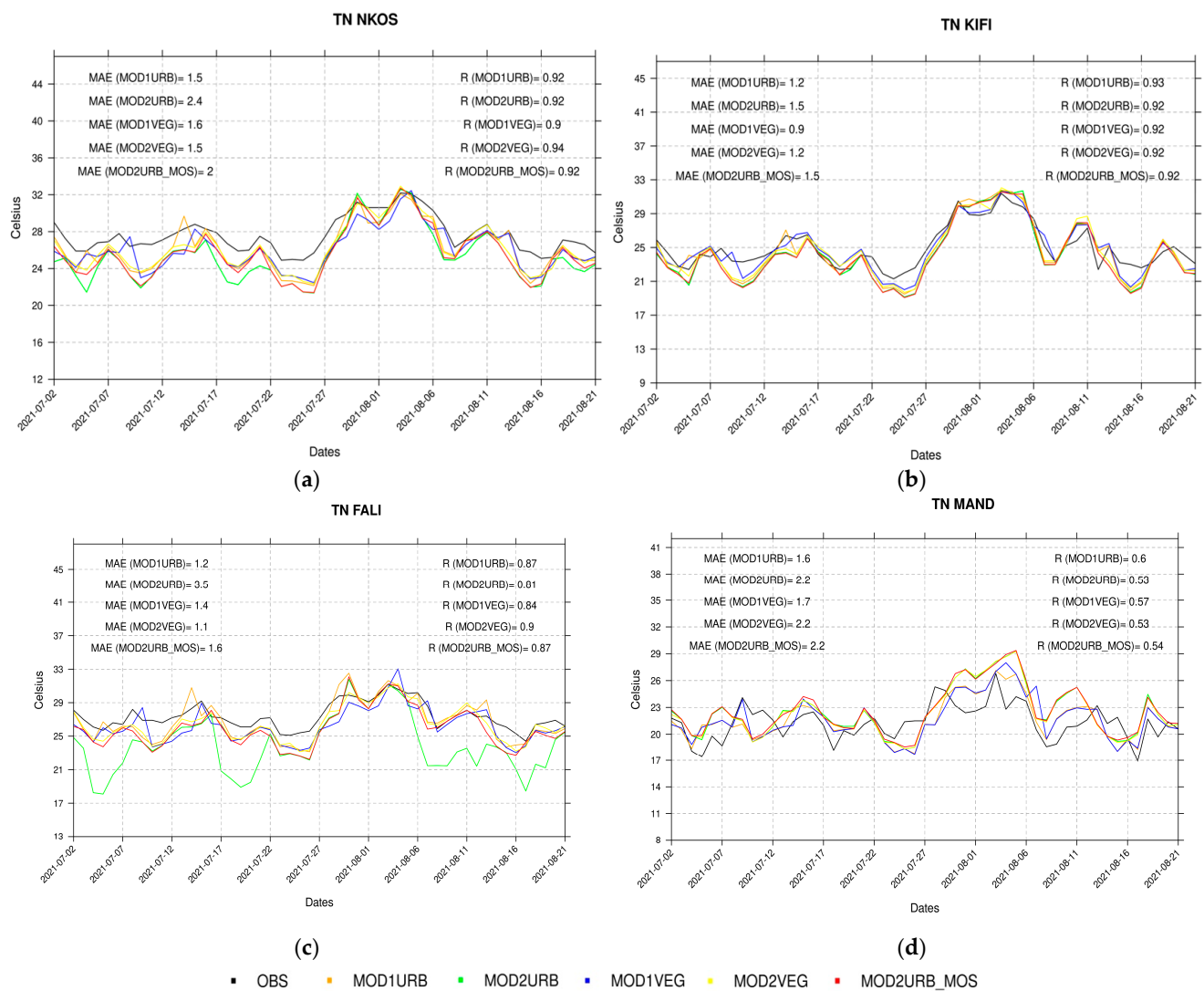


Figure 4. Observed and simulated T_{min} time series of the five different WRF Schemes vs. OBS at 4 METEO stations, NKOS (a), KIFI (b), FALI (c), and MAND (d) over the test period (1 July–20 August 2021).

Table 2. Validation metrics (R and MAE) for the five WRF schemes tested against in-situ data.

MAE	MOD1URB	MOD1VEG	MOD2URB	MOD2URB_MOS	MOD2VEG
Tmax All Stations	2.31	2.54	1.46	1.40	1.64
Tmax Urban	2.08	2.37	1.36	1.34	1.58
Tmin All Stations	1.64	1.66	2.05	1.62	1.55
Tmin Urban	1.45	1.41	1.92	1.45	1.35
R	MOD1URB	MOD1VEG	MOD2URB	MOD2URB_MOS	MOD2VEG
Tmax All Stations	0.82	0.80	0.90	0.92	0.92
Tmax Urban	0.83	0.82	0.91	0.93	0.90
Tmin All Stations	0.79	0.78	0.77	0.77	0.78
Tmin Urban	0.82	0.81	0.81	0.81	0.82

The model's forecasting skill for the daily minimum temperature (T_{min}) is slightly less accurate, reflected by lower values of the correlation coefficient R. Differences between physical parameterization schemes are less pronounced, with R ranging from 0.77 to 0.79 (Table 2) for all schemes, slightly increasing when the correlation with urban stations is

separately considered (0.81–0.82). Regarding model bias, MAE for $T_{\min}$ is comparable to $T_{\max}$, in the order of 1.5 °C for all WRF schemes, with the exception of MOD2URB, which exhibits a higher bias (MAE = 2 °C). Overall, the bias of the model compared to the in-situ observations is satisfactory and well within the acceptable limits of the associated model and instrumentation uncertainties.

Differences in WRF forecasting skills are also observed between types of stations (i.e., coastal vs. periurban vs. urban). Model output at coastal stations overall exhibits a lower correlation with the observational dataset than urban or periurban locations for both $T_{\max}$ and $T_{\min}$. This is also true for model bias, which is higher at coastal and periurban stations and lower at urban locations for both $T_{\max}$ and $T_{\min}$. Figure 5 illustrates the model validation metrics of $T_{\max}$ for different station categories with the optimal scheme (MOD2URB_MOS).

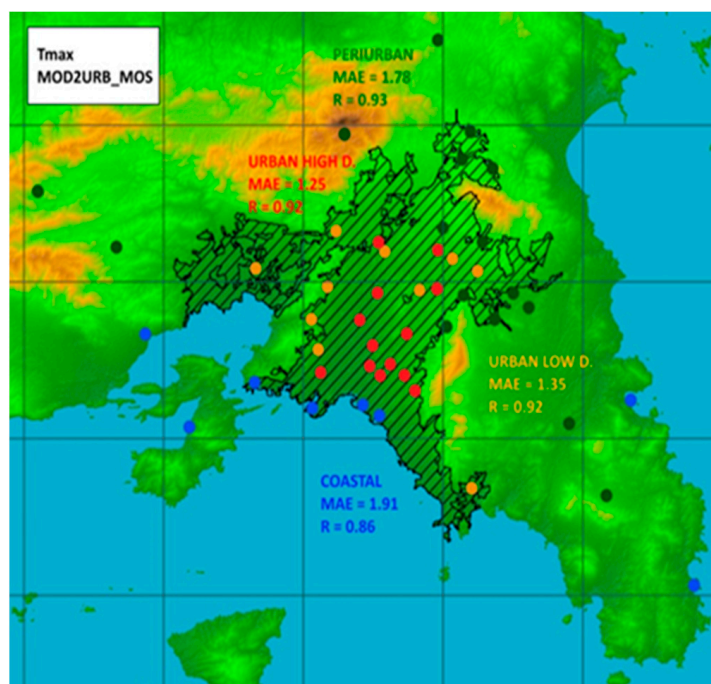


Figure 5. Map of the inner domain (d04), showing validation metrics of $T_{\max}$ for different station categories with the MOD2URB_MOS scheme.

3.2. Visualisation of Results and High-Resolution Mapping of the Urban Heat Island (UHI) Effect in the Athens Metropolitan Area

For the high-resolution mapping of the UHI effect in Athens, we utilise both the gridded observational dataset and the WRF output as described in the materials and methods section. A comparison between the two offers us a great deal of information about the model performance, the intensity of the UHI effect under different meteorological conditions, and the effect of the topography and urban spread on local temperature gradients. In Figure 6, in-situ and WRF simulated 1-km horizontal grid maps of maximum temperatures ($T_{\max}$) are presented for a three-day period (29–31 July 2021) when temperatures reached more than 40 °C during the heatwave. The WRF schemes shown are MOD2URB_MOS (being the one with the best overall performance) and MOD1URB. Areas of intense daytime UHI effect are clearly depicted in central as well as western parts of the urban complex in the observational grid, which are reproduced with a high degree of accuracy by the WRF simulation, particularly by the MOD2URB_MOS WRF scheme. The daytime UHI intensity during the first two days is estimated at 5–6 °C between central urban parts and the surrounding peri-urban areas.

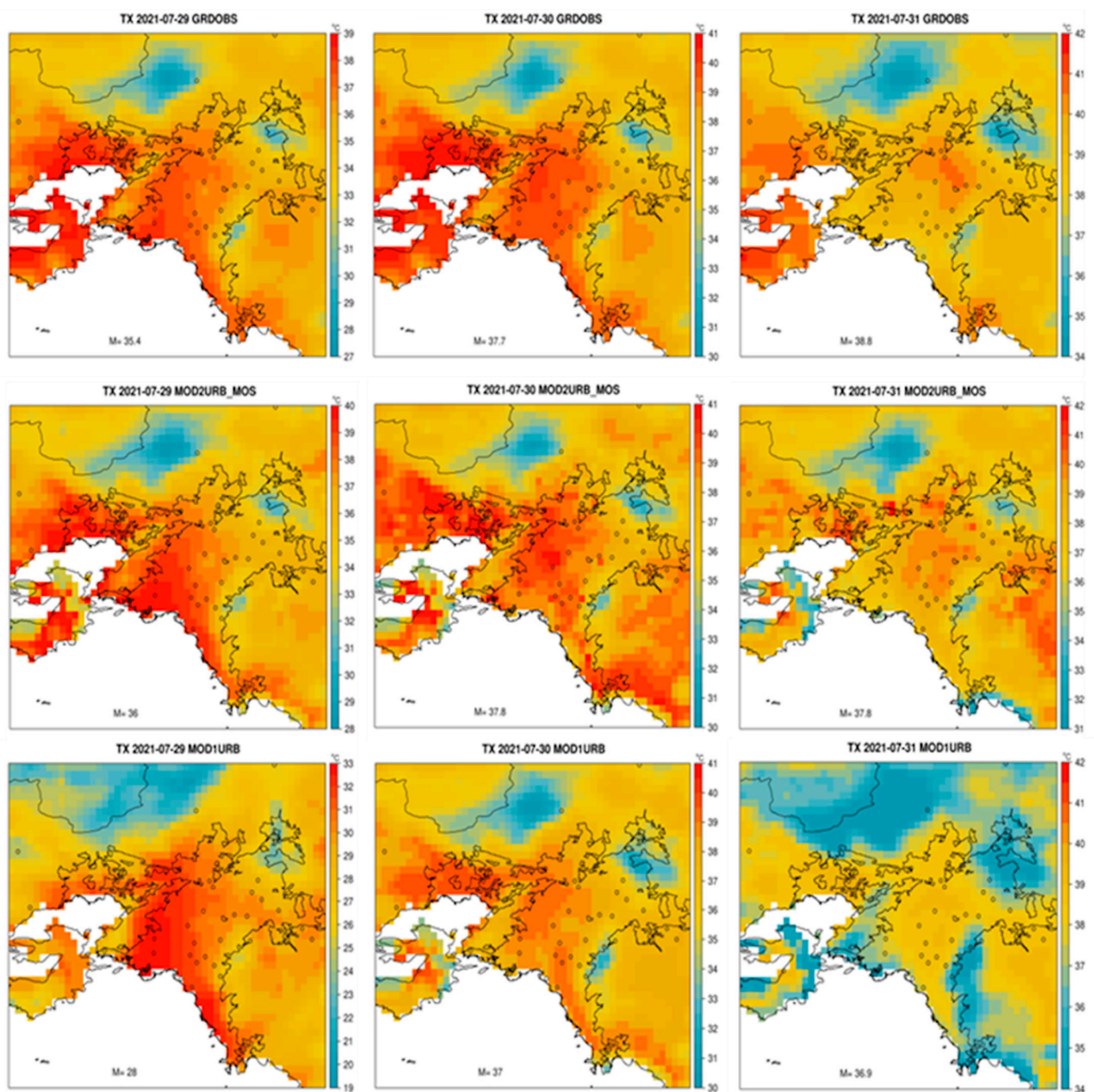


Figure 6. Observed (**top row**), WRF with MOD2URB_MOS scheme (**middle row**), and WRF with MOD1URB scheme (**bottom row**) high-resolution maps of $T_{\max}$, showing daytime temperature gradients and UHI intensity in the Greater Athens Area. Period covered is 29–31 July 2021, during the heatwave. Stations that provided in-situ data are marked (black circles).

After many consecutive hot days, the daytime temperature gradient seems to be spatially more uniform across the urban complex (day 3), and background maximum temperatures are becoming increasingly hotter. As a result, the daytime UHI intensity on 31 July is estimated at 4 °C between central urban parts and the surrounding periurban areas.

In Figure 7, in-situ and WRF simulated (1-km grid) maps of minimum temperatures ($T_{\min}$) are presented for the same three-day period (29–31 July 2021). The $T_{\min}$ temperature gradient is again intense, revealing a pronounced UHI effect during the night hours. Central and southern coastal parts are mostly affected by high $T_{\min}$ temperatures, which

are possibly the result of nighttime thermal air circulation (land breeze), cooling down the central and northern parts of Athens. The two WRF schemes are again accurately simulating both the spatial distribution and magnitude of $T_{\min}$, but to a lesser degree compared to $T_{\max}$.

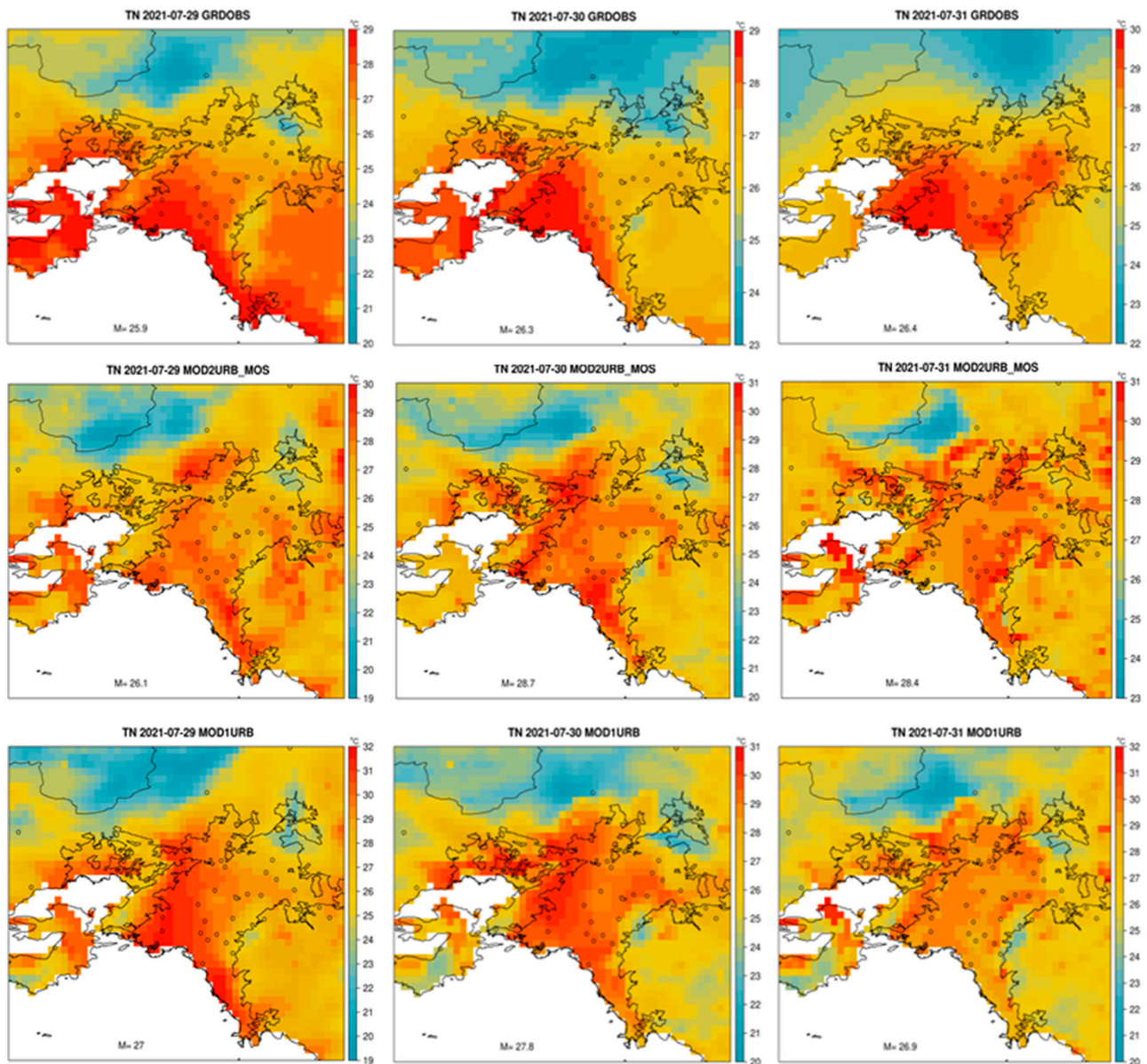


Figure 7. Observed (**top row**), WRF with MOD2URB_MOS scheme (**middle row**), and WRF with MOD1URB scheme (**bottom row**) high-resolution maps of $T_{\min}$, showing nighttime temperature gradients and UHI intensity in the Greater Athens Area. Period covered is 29–31 July 2021, during the heat wave. Stations that provided in-situ data are marked (black circles).

Evidently, an overestimation of minimum nighttime temperatures is produced by the MOD1URB scheme on the first day (29 July) and by both WRF schemes on the second day (30 July). Nighttime UHI intensity is estimated at 4–5 °C between central urban parts and the surrounding peri-urban areas.

When we look at the model bias, it is evident that WRF performs well and accurately reconstructs temperature gradients, particularly under typical summer conditions. Figure 8 illustrates model bias against in-situ gridded data of $T_{\max}$ for three different WRF schemes during a three-day period with seasonally average high temperatures (8–10 July 2021). Both

schemes with the MOD2 physical parameterization perform satisfactorily, and bias does not exceed 1–2 °C within the urban section. The scheme with the MOD1 physical parameterization performs less accurately, as model bias is shown to increase by 1 °C within the metropolitan area compared to the MOD2 parameterization. Similarly, Figure 9 illustrates the model bias of $T_{\max}$ for the same schemes during a three-day period with above-average high temperatures (29–31 July 2021). During heat wave conditions, model bias is still low (between 0.5 °C and 2.5 °C) within the city limits for MOD2, slightly increasing with the MOD1 parameterization. Generally, the model tends to underestimate $T_{\max}$ temperatures in most cases, with an exception during very hot days (i.e., 30–31 July). It is important to note that spatial interpolation of in-situ data is more accurate and representative of actual surface temperatures within the urban structure due to the higher density of ground stations. Therefore, WRF validation with in-situ gridded data and bias estimation is more reliable in this area.

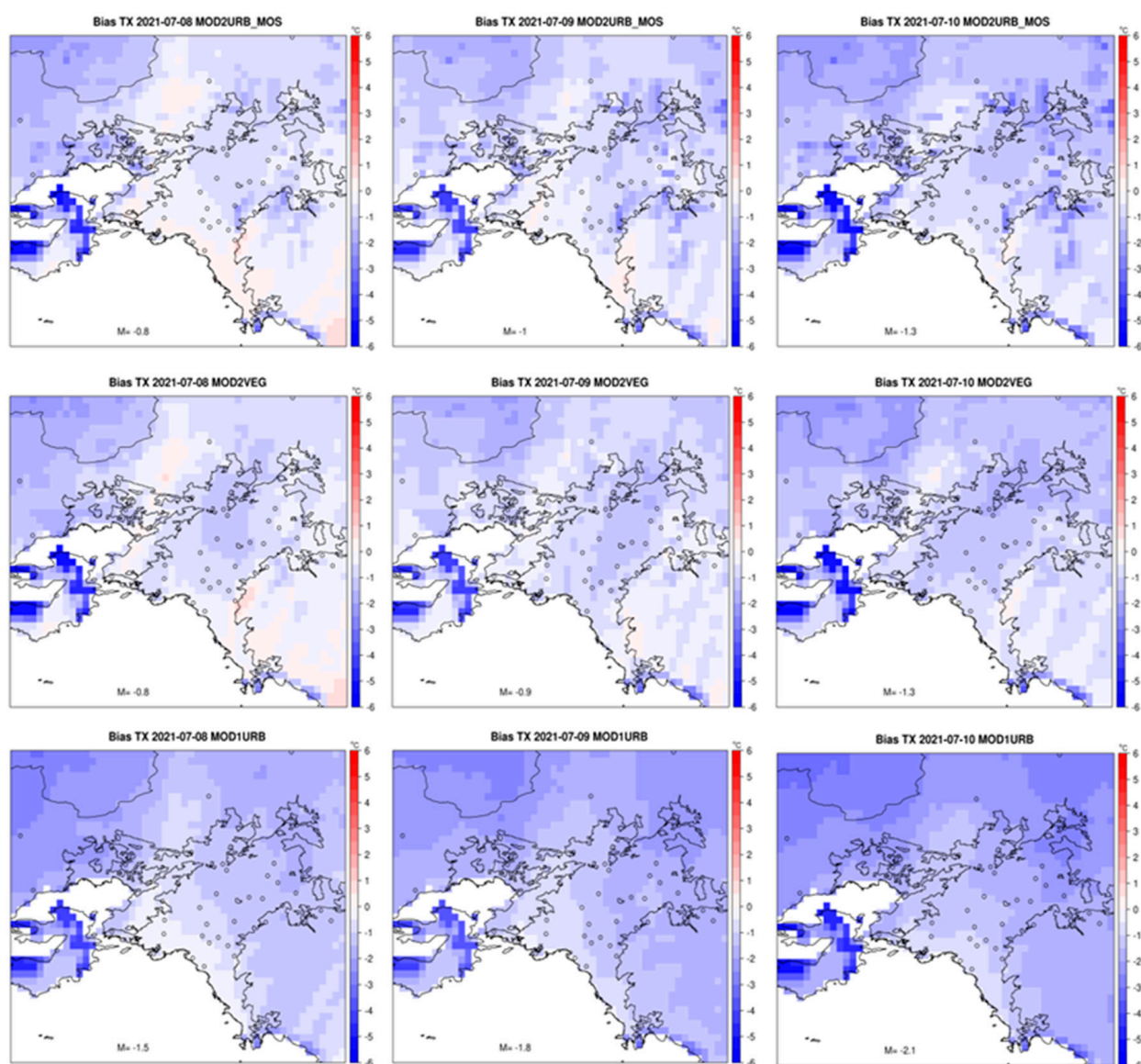


Figure 8. Model bias against in-situ gridded data of $T_{\max}$ for three WRF schemes, MOD2URB_MOS (top row), MOD2VEG (middle row), and MOD1URB (bottom row). Period covered is 8–10 July 2021, during which moderately high temperatures are observed (approximately 35 °C, typical of the summer period). Stations that provided in-situ data are marked (black circles).

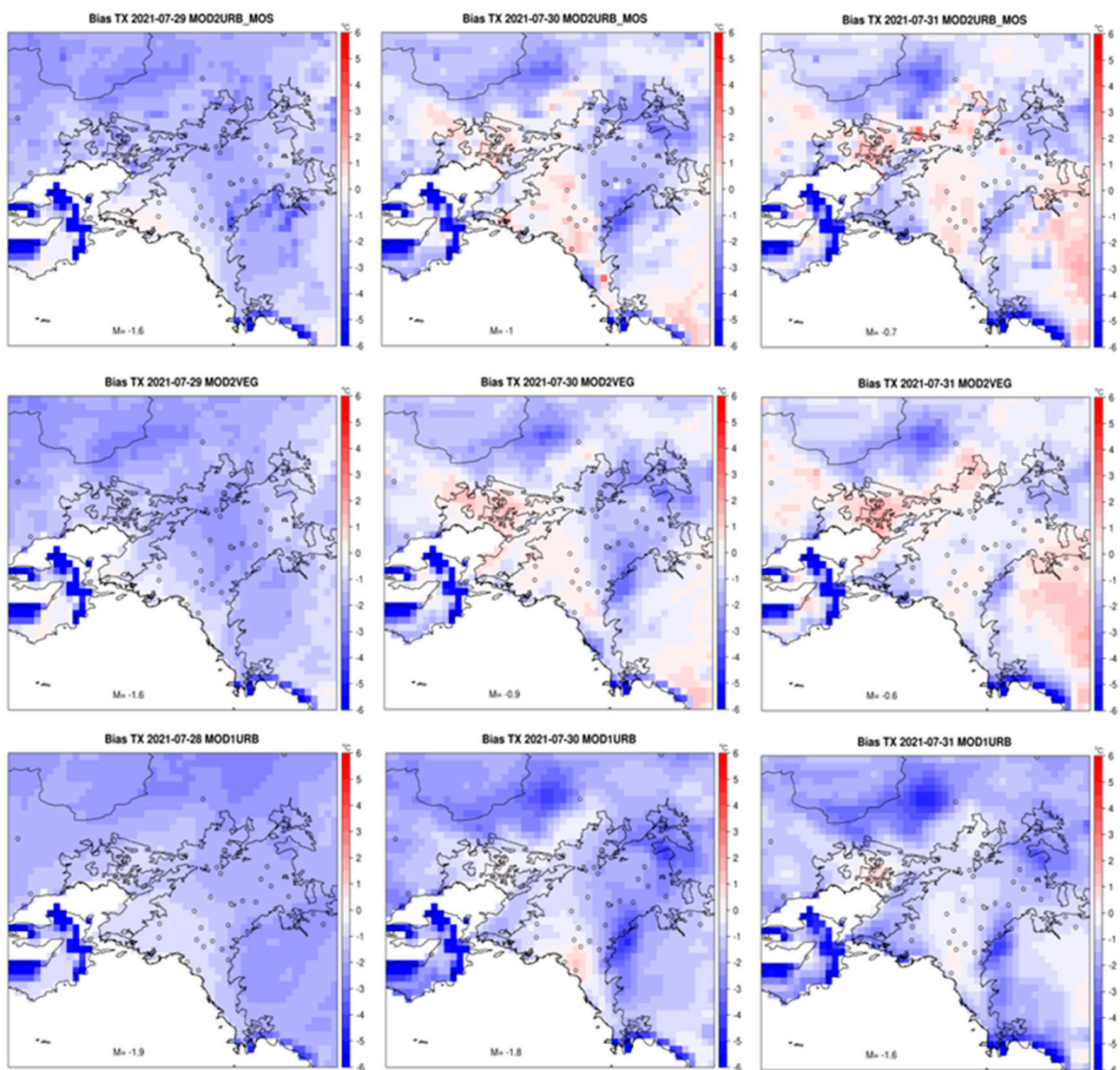


Figure 9. Model bias against in-situ gridded data of $T_{\max}$ for three WRF schemes, MOD2URB_MOS (top row), MOD2VEG (middle row), and MOD1URB (bottom row). Period covered is 29–31 July 2021, during which extreme daily high temperatures are observed ($>40^{\circ}\text{C}$, heatwave conditions). Stations that provided in-situ data are marked (black circles).

3.3. Daily Progression of the UHI Effect in Athens—UHI Intensity

Having analysed the experimental results and model output with respect to $T_{\max}$ and $T_{\min}$ temperatures, it is now interesting to examine the diurnal characteristics of the UHI effect in Athens with the use of high-resolution surface temperature maps produced by the WRF model. In fact, it is possible to demonstrate how the UHI effect evolves on an hourly basis in great detail and how the local microclimate changes under different weather conditions and local air circulation patterns. Here, we present a case study of the diurnal UHI progression for two consecutive days during the heatwave of 28 July–5 August 2021. Figure 10 illustrates a three-hour lapse of T_2 temperatures in the whole of Attiki Region (metropolitan Athens and surrounding areas) produced by WRF (MOD2URB_MOS scheme) on the 1 August, with wind vectors also included on the maps. The UHI effect is already clearly visible in the early morning hours as the heat contained in the built environ-

ment from the previous day is gradually dissipated back into the environment. At 07:00, temperatures had already reached 32 °C in parts of central Athens. During the afternoon hours, the UHI effect is less intense, as a slight S-SW sea-breeze cools down the southern and central urban districts of Athens. Temperatures reach 40–41 °C in the city centre, but there is no significant temperature gradient between central and periurban districts. In the evening hours, the UHI effect is again more noticeable, as in the absence of solar radiation, periurban vegetated areas cool down faster than high-density urban districts.

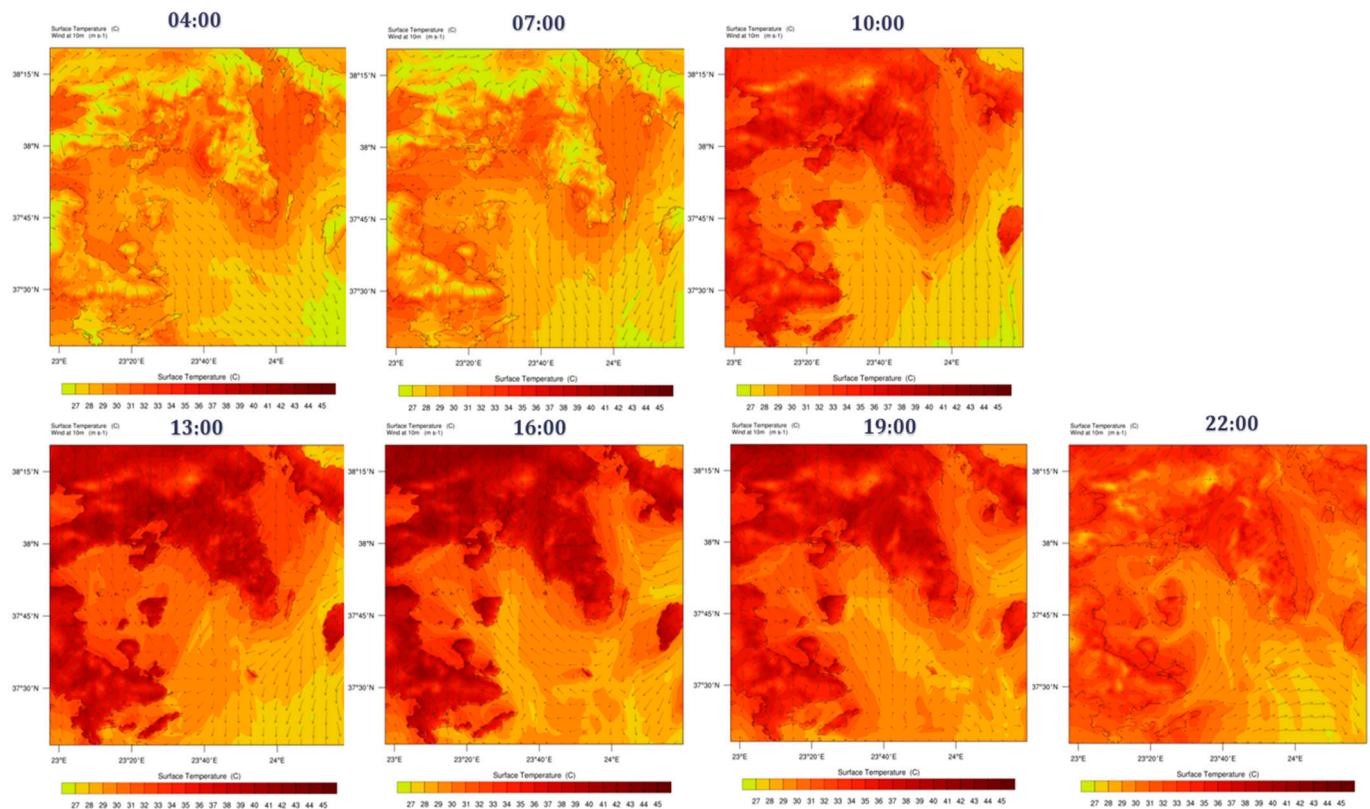


Figure 10. Three-hour lapse of T2 temperatures in Attiki produced by WRF (MOD2URB_MOS scheme) on 1 August 2021. The UHI effect is visible during morning hours as high-density urban areas emit heat absorbed during the previous day back into the environment. During afternoon hours, a slight southern sea breeze cools down the coastal front of the metropolitan area. The UHI effect is not as intense during the day; however, there is a noticeable temperature gradient between central and periurban districts during the evening hours.

Figure 11 illustrates a similar three-hour lapse of T2 temperatures in the whole of the Attiki Region (metropolitan Athens and surrounding areas) produced by the WRF (MOD2URB_MOS scheme) on the following day (2 August). Morning temperatures are higher than the previous day (up to 34 °C), and the UHI effect is visibly more intense during the course of the day, as a slight northern wind does not reach the central parts of Athens, where temperatures remain very high compared to the background. A 6–7 °C temperature gradient between central and periurban districts is clearly visible during afternoon and evening hours, as the heat content absorbed by the built environment after consecutive days of intense solar radiation cannot be dispersed.

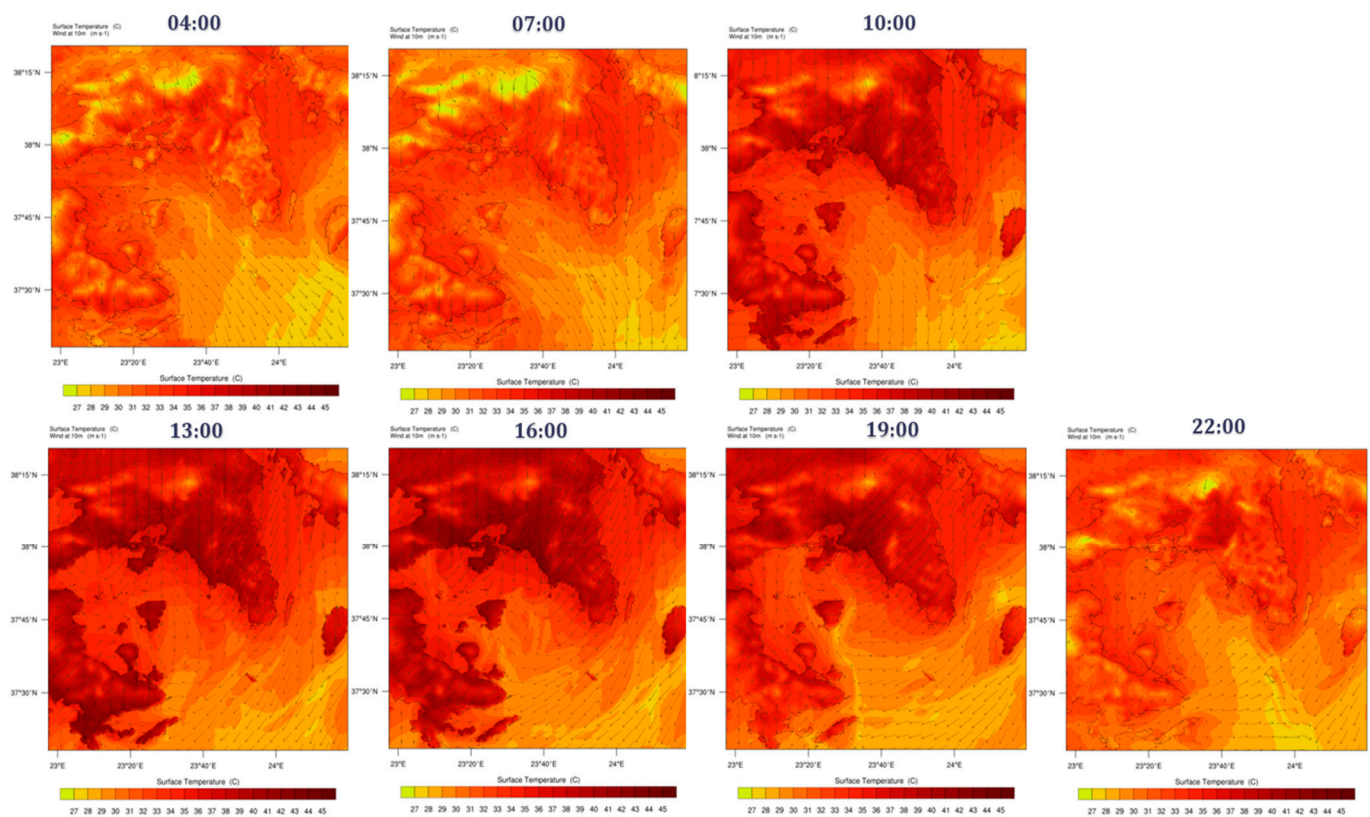


Figure 11. Three-hour lapse of T2 temperatures in Attiki produced by WRF (MOD2URB_MODS scheme) on 2nd August, 2021. The UHI effect is visibly more intense than the previous day, as a slight northern wind during the course of the day cannot reach the central parts of Athens, where temperature remains very high compared to the background. A 6–7 °C temperature gradient between central and periurban districts is clearly visible during afternoon and evening hours, as the heat contained inside the urban environment after consecutive days of intense solar radiation cannot be dispersed.

4. Discussion

Results of the sensitivity analysis indicate that WRF schemes with MOD2 physics (MO Eta-Janjic similarity surface layer coupled with MYJ boundary layer) overall exhibit a better prediction skill of daily maximum temperatures ($T_{\max}$) during the 50-day test period ($R > 0.9$, $MAB < 1.5$ °C), compared to WRF schemes with MOD1 physics (MM5 similarity surface layer coupled with YSU boundary layer). However, with respect to predicting daily minimum temperatures ($T_{\min}$) there is no significant difference between the two physical parameterizations, which exhibit similar validation metrics for correlation and bias ($R \approx 0.8$, $MAB < 2$ °C). Planetary boundary layer (PBL) physics can have a strong effect on WRF output due to differences in modelling vertical eddy diffusivities, surface energy budgets, and tracer concentrations (e.g., water vapour) in the lower troposphere. In a study comparing the effect of the two PBL schemes on WRF output parameters [58], it was shown that the Yonsei University (YSU) scheme simulated higher air temperatures and a weaker nighttime surface-based inversion layer than the Mellor-Yamada-Janjic (MYJ) scheme, due to increased entrainment at the top of the boundary layer and vertical mixing in the Yonsei University (YSU) scheme. Differences in the estimation of wind profiles with different PBL schemes have also been reported [59], with simulations using nonlocal PBL schemes (such as YSU) showing an overestimation of the vertical wind speed component at a height of 250 m from the surface due to excessive vertical mixing in the boundary layer. Similar findings are reported [60] in an investigation of the impact of PBL schemes on the simulation of vertical wind structures with the WRF model. It is confirmed that

boundary layer schemes in the WRF model can simulate significantly different wind fields, with complex topographies producing larger errors. It is shown that the MYJ scheme produces more accurate wind profiles than YSU under conditions of low wind speed (under 5 m s^{-1}) at heights below 300 m on sunny days. Our results are consistent with these reports, indicating that during daytime, under hot and stable boundary layer conditions, the estimation of the surface temperature with WRF is more accurate with the MYJ PBL scheme, while during nighttime, a shorter duration of the inversion layer by the YSU scheme (up to 4 h shorter than MYJ) [58] may compensate for the lower bias of $T_{\min}$ with respect to $T_{\max}$ estimation.

Furthermore, it is demonstrated that the effect of physical parameterization is stronger than the effect of the urban canopy parameterization on WRF output with regard to predicting T_2 temperatures. Schemes MOD1URB and MOD2URB, which use the Single Layer Urban Canopy Model (SLUCM), exhibit slightly improved validation metrics with regards to $T_{\max}$ (mean absolute bias is 10% and 12% lower for MOD1 and MOD2, respectively) than schemes MOD1VEG and MOD2VEG, where the Urban Canopy Model is turned off. When the mosaic subtiling option is turned on in the MOD2URB_MOS scheme, $T_{\max}$ bias is even lower (15% lower than MOD2VEG). On the contrary, a marginal difference is observed with respect to $T_{\min}$ prediction between the MOD1URB and MOD1VEG schemes, whereas the $T_{\min}$ bias of MOD2URB increases by 32% compared to MOD2VEG, but only 4% with the MOD2URB_MOS scheme.

High-resolution UHI mapping with WRF in the Greater Athens Area presents varying degrees of spatiotemporal temperature variability and gradient distribution across different parts of the city, depending on the prevailing weather characteristics. Under heat wave conditions and in the absence of strong air circulation (e.g., 29–30 July 2021), areas of intense daytime UHI effect are observed in densely built central as well as western parts of the urban complex in the observational gridded dataset, which are reproduced with a high degree of accuracy by the WRF simulation. Daytime UHI intensity is estimated at $5\text{--}6^\circ\text{C}$ between central urban parts and the surrounding periurban areas. In the presence of S-SW air circulation (sea-breeze), a cooling effect is observed in southern and central urban districts of Athens, and the UHI intensity is limited at $3\text{--}4^\circ\text{C}$ (e.g., 1 August 2021). The maximum UHI intensity is observed during evening hours under heat wave conditions, when a $6\text{--}8^\circ\text{C}$ UHI magnitude is observed (e.g., 2 August 2021), as the heat absorbed by the built environment after consecutive days of intense solar radiation is released by long-wave radiative processes during nighttime, while in the absence of solar radiation, suburban vegetated areas cool down faster than high-density urban districts. Our results are consistent with previous research findings [16,19,20], which suggest similar daytime and nighttime UHI intensities in Athens.

5. Conclusions

The methodological approach followed aims to maximise the potential of using high-resolution WRF modelling for mapping the UHI effect in large metropolitan complexes. Five different WRF parameterization schemes are examined, ranging from schemes with relatively simple physical and urban canopy parameterization to more complex schemes that require longer computational times. A sensitivity analysis is performed for a fifty-day period (1 July–20 August 2021), during which the model output is validated with the use of in-situ data from 48 permanent stations in the study area (d04). The results are tested for their statistical significance and demonstrate that the MOD2URB_MOS scheme is the one with the best overall performance. With respect to $T_{\max}$ temperatures, results exhibit a strong correlation between WRF and in-situ data. Correlation R is higher than 0.9 for the best parameterization schemes, while bias (expressed as mean absolute error) is in the region of 1.5°C and even lower when the urban extension is considered separately. With respect to $T_{\min}$ temperatures, correlation R is lower (0.8 for most schemes; differences between physical parameterization schemes are less pronounced), indicating that nighttime temperatures are not predicted equally well by the model. However, bias

is again satisfactory (approximately 1.5 °C for most WRF schemes) and well within the acceptable limits of associated model and instrumentation uncertainties. Furthermore, it is shown that the effect of physical parameterization is stronger than the effect of the urban canopy parameterization on WRF output with regards to predicting T2 temperatures and that the Mosaic LC option improves output in most cases.

High-resolution UHI mapping in Athens reveals different degrees of temperature variability and gradient distribution depending on local weather patterns. Under heat wave conditions and in the absence of strong air circulation, areas of intense daytime UHI effect are observed in central as well as western parts of the urban complex in the observational gridded dataset, which are reproduced with a high degree of accuracy by the WRF simulation. Maximum daytime UHI intensity is estimated at 5–6 °C between central urban parts and the surrounding periurban areas. On the other hand, a maximum 6–8 °C UHI magnitude is clearly visible during evening hours, as the heat content absorbed by the built environment after consecutive days of intense solar radiation is released by long-wave radiative processes during nighttime. Our results are consistent with previous research findings [16,17,19,20], which suggest similar daytime and nighttime UHI intensities in Athens.

Overall, the current study demonstrates the high potential and effectiveness of using high-resolution WRF modelling for urban studies and UHI mapping. The innovative elements that our methodology brings in comparison with previous studies are: (a) High-resolution reanalysis with WRF: The model is downscaled at 1-km horizontal resolution and therefore offers a detailed reconstruction of temperature gradients over the study area. The model is locally configured and parameterised with the Urban Canopy Model according to specific surface and activity characteristics for the city of Athens, and different complex schemes are tested in order to demonstrate the optimal configuration. (b) Validation of the model: WRF output is validated with the use of in-situ data retrieved from a dense array of meteorological stations covering the study area. Model validation is performed against in-situ data at the nearest grid point, but also against a gridded dataset resulting from the spatial interpolation of observations. The results provide a comprehensive assessment of spatiotemporal variations of the UHI effect in a large metropolitan complex such as GAA, expanding on previous research findings and enabling the UHI magnitude under different meteorological conditions and the effect of the topography and urban spread on local temperature gradients to be accurately quantified. Further work will focus on testing additional parameterization schemes and incorporating the research outcome into the forecasting of extreme heat events in urban areas and urban climatic studies.

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