

Enhancing urban microclimate simulations: Validating ENVI-met's accuracy in modeling multi-directional radiative fluxes and mean radiant temperature in subtropical hong kong

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ARTICLE INFO

Keywords:

Model validation
Albedo
Cloud parameterization
Shortwave radiation
Longwave Radiation
Thermal Comfort

ABSTRACT

Urban microclimate modeling requires precise simulation of shortwave (SW) and longwave (LW) radiative fluxes to accurately determine thermal comfort via mean radiant temperature (MRT). This study evaluates the performance of ENVI-met in simulating six-directional radiative fluxes and diurnal MRT in a high-density city under its subtropical cloudy conditions, specifically at Oi Man Estate in Kowloon City, Hong Kong. Measurements were conducted on three separate days of intense heat – July 29, August 15, and August 23, 2022 – from 09:30 to 17:00. The model configuration was calibrated for different site settings, including unshaded urban areas and areas with various shading types. Through iterative refinements of empirical albedo calibration and cloud approximation significant improvements in model accuracy were achieved. For incoming SW radiation, RMSE in Open Space decreased by 78 % (from 201.82 to 44.29 Wm⁻²) between initial and optimized simulations, with R² reaching 0.984. Using site-specific inputs and optimized configurations, including calibrated surface albedo and a mid-level cloud approximation, the model's MRT estimates improved markedly across all sites and scenarios (mean RMSE = 2.62 K; R² = 0.73). These findings offer actionable insights for refining urban climate models and highlight the critical importance of input parameter calibration in complex urban morphology. Contrary to earlier studies, this study showed no systematic MRT underestimations in shaded areas. The results demonstrate ENVI-met's capability to resolve spatially variable radiative fluxes when critical inputs are empirically constrained, enabling reliable area-wide diurnal MRT analysis.

Introduction

Urban overheating has become a pervasive stressor in densely built environments, as the arrangement of buildings and infrastructure leads to variations in temperature, airflow, and humidity and thereby diminishes thermal comfort and compromises the wellbeing of city dwellers [1]. Among the drivers of these heat burdens, the outdoor radiant environment is decisive, particularly in low-latitude cities where solar radiation is intense [2]. These localized conditions can contribute to phenomena such as urban heat islands, which increase energy demands and pose health risks during extreme weather [3,4]. One key metric in assessing thermal comfort in such environments is the mean radiant temperature (MRT), which offers a quantitative description of

the environment by integrating the shortwave (SW) and longwave (LW) exchanges between the human body and surrounding surfaces, thereby directly governing perceived heat load [5–9]. Consequently, accurate characterization of MRT is indispensable for diagnosing urban thermal discomfort and for guiding climate-sensitive design and mitigation strategies.

To accurately describe MRT and understand its effects on the human body, it is essential to consider the direction of the incoming radiation flux, as the human body presents varying projection areas depending on the radiation's angle [10]. Upon reaching urban surfaces, SW radiation is modulated by surface albedo, a parameter notably affected by material composition and aging processes [11,12]. In contrast, LW radiation, governed by surface emissivity and sky view factors, plays a pivotal role

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<https://doi.org/10.1016/j.buildenv.2025.113475>

Received 7 May 2025; Received in revised form 20 July 2025; Accepted 22 July 2025

Available online 23 July 2025

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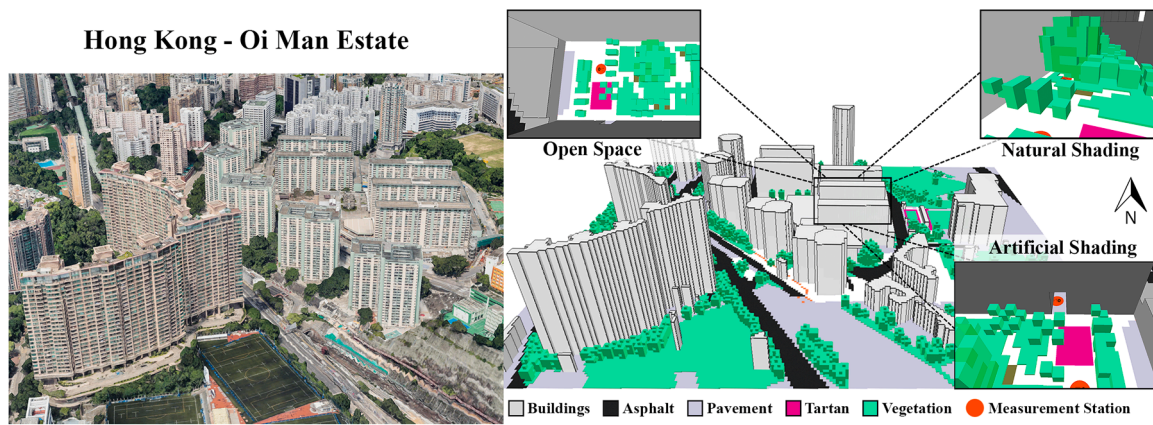


Fig 1. Model area depicted in Google Earth and ENVI-met Spaces, featuring an overview of the measurement sites.

in nocturnal cooling [13,14]. The MRT is often used to encapsulate the effects of these radiative fluxes, as it provides a comprehensive measure of the thermal environment impacting human comfort [15]. This approach requires six-directional measurements (up, down, north, east, south, west), which are complex and resource-intensive to conduct but offer superior precision and reliability compared to traditional black globe thermometer measurements, providing a better assessment of radiative influences on thermal comfort [7,16,17]. As a result, there is a scarcity of such comprehensive data [17–19].

Because direct measurement of radiation fluxes is equipment-intensive and time-consuming, numerical simulation provides a practical alternative for estimating MRT. Several microscale models, such as RayMan and SOLWEIG, integrate urban geometry with radiative transfer algorithms to simulate the outdoor radiant environment and derive pedestrian-level MRT [20,21]. Distinct from these, ENVI-met couples a full three-dimensional computational fluid dynamics (CFD) solver with detailed building and vegetation modules, enabling meter-scale simulations that capture the combined effects of wind, humidity, greenery, and surface heat fluxes on MRT within complex urban morphologies [22–24]. Its ability to model the intricate interplay between surface geometry, vegetation, and atmospheric processes makes ENVI-met highly valuable for assessing the impact of urban form on thermal comfort, while its high spatial resolution and dynamic simulation capabilities allow researchers and planners to explore urban design scenarios and evaluate mitigation strategies for heat island effects [24,25]. Sinsel et al. (2022) [26] have carried out a calibration and refined the method on MRT simulation in ENVI-met, achieving promising, although not perfectly accurate, results. Subsequently, a series of more recent studies have been conducted examining ENVI-met's new MRT implementation. While they yielded good results they also were not entirely satisfactory (see also Section 4.2 in the Discussion) [18,27–29].

With the insights provided by the previous work on model calibration, however, it remains a question whether the limitations of the computing results of ENVI-met are due to the accuracy of the model itself, suggesting that radiative flux and/or MRT calculations may not yet be correctly implemented, or whether it is inherently challenging to measure and model these parameters accurately. In this regard, this study seeks to validate and refine ENVI-met's MRT module by employing the most comprehensive measurement protocol, i.e. simultaneously recording six-directional radiative fluxes at various urban sites, and by calibrating the model with real-time weather data and site-specific building parameters, thereby enhancing its simulation accuracy. SW and LW radiative fluxes were recorded in all six directions (up, down, north, east, south, west) in three distinct and highly-complex urban settings in Hong Kong: an unshaded plaza, a tree-shaded area, and a semi-enclosed building corridor. By comparing field measurements with simulation outcomes from progressively refined models, this research seeks to enhance the understanding of ENVI-met's capability to

accurately simulate radiative fluxes and hence MRT.

2. Methodology

This study is centered on the validation of microclimate simulations using the ENVI-met model within a highly complex urban environment in Hong Kong. The core urban areas in Hong Kong present a high-density, high-rise morphology, typified by rather low sky view factor values (< 0.2) within many street canyons [30]. The resulting three-dimensional morphology generates intricate patterns of solar obstruction and multiple reflections of both SW and LW radiation. These geometric interactions create steep spatial gradients in MRT across the scales of building blocks, resulting in an exceptionally complex radiant environment that challenges conventional urban microclimate models [31].

Additionally, Hong Kong presents a subtropical climate that is dominated by frequent, rapidly evolving cloud cover during the summer season [32]. These fluctuating low- and mid-level clouds modulate incoming SW and outgoing LW radiation, thereby creating highly dynamic radiant environments. This spectrum of sky conditions offers an opportunity for empirical assessment of ENVI-met's cloud-radiation scheme. With high-resolution measurement data capturing this temporal diversity, the present study can evaluate the model's ability to reproduce cloud-induced swings in MRT and refine its parametrization for subtropical megacities like Hong Kong. Previous research conducted in this region, including studies by Cheng et al. (2023) [33], Jia and Wang (2021) [34], Lan et al. (2021) [35], Ma et al. (2024) [36], Morakinyo et al. (2020, 2018, 2017) [37–39], Ng et al. (2012) [40], Ouyang et al. (2025, 2024) [41,42], highlighted the challenges associated with accurately replicating MRT due to the intricate interactions of SW and LW radiation, particularly in such a multifaceted setting. The six-directional measurements are crucial for capturing these interactions accurately, as they provide detailed insights into the role of reflected SW radiation, which is vital for validating simulation results in densely constructed urban environments. These complexities underscore the necessity of precise modeling to understand and predict microclimatic phenomena in Hong Kong.

2.1. Study area and measurement sites

The study area is situated within the Oi Man public housing estate (22.3114°N, 114.1792°E) in Kowloon City, Hong Kong. Constructed in 1974, the estate is classified as Local Climate Zone 1 (LCZ1: compact high-rise), featuring uniform residential towers that create a tightly woven urban fabric. The area exhibits a high building coverage ratio of 0.76 and limited vegetation, with an normalized difference vegetation index (NDVI) of 0.46 [42]. This site exemplifies Hong Kong's compact urban morphology, characterized by mid-rise residential towers and

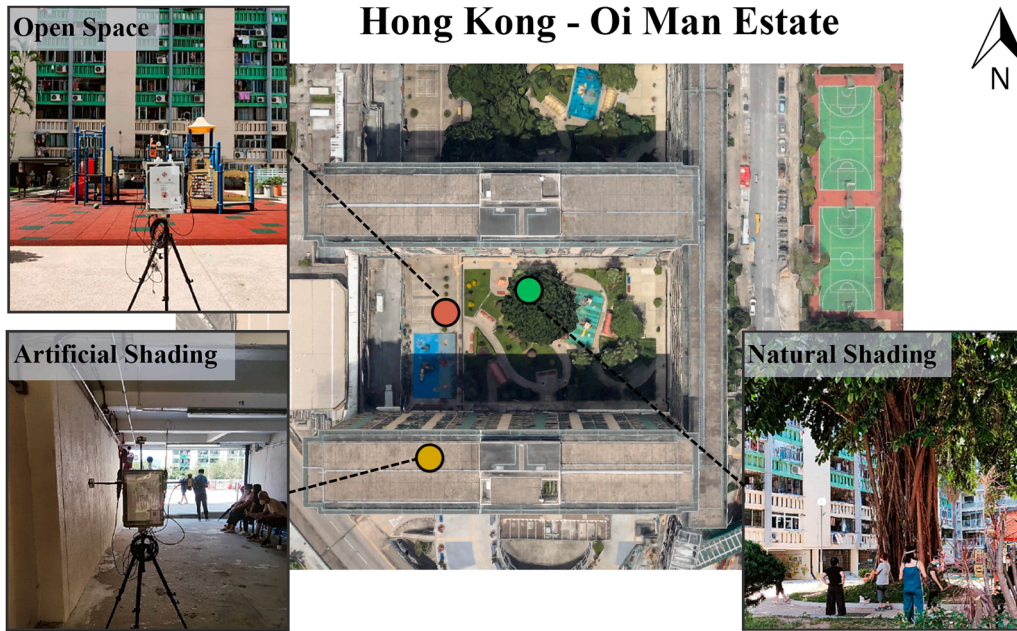


Fig 2. Locations of the three measuring stations within the model area, represented in Google Earth.

Table 1
Summary of the simulation parameters.

General Properties	Hong Kong Oi Man Model Area
Start Date and Time (Local)	2022-07-28 09:00, 2022-08-14 09:00, 2022-08-22 09:00
Duration	33 h
Meteorological Boundary Conditions	Full Forcing
Roughness length	0.19 m
Location Latitude (Lower Left Corner)	22.30899° N
Location Longitude (Lower Left Corner)	114.17579° E
Dimensions	215 × 187 × 34
Resolutions (X,Y,Z)	3 × 3 × 3 m
Lowest Grid Cell Split	Yes
Telescoping: Factor and Starting Height	20 % above 60 m
Surface Steps [s]	30
Radiation Steps [s]	300

limited vegetation (Fig. 1).

Within this context, three distinct environments were selected to provide a comprehensive evaluation of shading strategies. The first site, referred to as Open Space, is a sun-exposed asphalt plaza that receives a significant amount of incoming SW radiation. This area is characterized by a lack of overhead protection, allowing direct solar radiation to predominate during daytime. The second site, Natural Shading, is situated beneath a mature *Ficus microcarpa* tree, a species known for its broad, dense canopy and ability to dispense organic cooling through shade and evapotranspiration. This site offers a stark contrast to the impervious surfaces dominating the estate, providing a natural mitigation strategy against heat. The third site, Artificial Shading, is a semi-enclosed corridor integrated into the residential complex itself. This site minimizes sky exposure and airflow, creating a unique microclimate where shading arises from the building's layered architecture rather than a simple roof. These highly diverse microclimates supply a wide range of shading scenarios necessary to evaluate the validity of simulation results across different conditions (Fig. 2). Our approach uses temporally synchronized measurements at three distinctly different urban sites as a proxy for assessing spatial model performance, given the

constraints of spatially continuous observational data.

2.2. Instrumentation and data collection

A combination of high-precision sensors were employed to capture microclimatic variables, with a particular focus on radiative fluxes. SW and LW radiation was measured using Apogee SN-500 four-component net radiometers, positioned at a height of 1.5 m to approximate human thermal exposure. These instruments were recalibrated on a roof podium at the Chinese University of Hong Kong prior to deployment, following the procedure outlined by Ouyang et al. (2021), to ensure high measurement accuracy and reliability for both SW and LW radiation [43]. Each radiometer was oriented to capture six directional fluxes: upward and downward vertical, along with the four cardinal directions. This configuration facilitates comprehensive calculations of the radiative balance, crucial for assessing MRT. Additionally, air temperature and relative humidity were monitored using Kestrel 5400 Heat Stress Trackers, calibrated against a reference station to minimize inter-device variability. The detailed specifics of the field measurements and equipment settings can be found in the measurement study conducted by Ouyang et al. (2024) [42]. MRT was accurately derived from the six-directional SW and LW radiation data using the method shown in Eq. (1) and (2) [44,45].

$$T_{mrt} = \sqrt[4]{S_{str}/(\epsilon_p \sigma)} - 273.15 \text{ K} \quad (1)$$

S_{str} represents the combined SW and LW fluxes from the six directions (Eq. (2)), ϵ_p is the absorption coefficient of the clothed human body (0.97), σ is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$), a_k the absorption coefficient for SW radiation, which is a standard value generally assumed to be 0.7, and F_i stands for the angle view factors (lateral directions = 0.22, upper and lower hemisphere = 0.06) for the measured SW (K_i) and LW radiation (L_i) based on the cylindrical shape of a standing human body [7,44].

$$S_{str} = a_k \cdot \sum_{i=1}^6 K_i \cdot F_i + \epsilon_p \cdot \sum_{i=1}^6 L_i \cdot F_i \quad (2)$$

Data collection was conducted on three non-consecutive days of intense heat, characterized by maximum air temperatures exceeding 33 °C, with data being collected between 9:30 and 17:00 each day. The

measured values are provided at ten-minute intervals to be able to represent the high variability of radiative fluxes at the measurement locations. In the Artificial Shading measurements, frequent negative SW values, likely due to calibration drift or sensor misalignment, necessitated adjusting all values by raising them by the difference between 0 Wm^{-2} and the most negative value to preserve diurnal trends and ensure reliable evaluation.

2.3. ENVI-met model setup

Nine simulations, covering three configurations across three days, were executed using ENVI-met Version 5.7.2, the newest version available to date, each spanning 33 h to encompass both spin-up and measurement phases (Table 1). The model area includes the three adjacent measurement sites within a single courtyard complex, embedded within an ENVI-met model domain spanning 645 m $\times$ 561 m horizontally and 273 m vertically (Fig. 1). This spatial extent was chosen to account for the radiative influence of surrounding high-rise buildings, whose shadows influence local SW and LW radiation fluxes. To balance computational efficiency with accurate representation of shadow dynamics, a grid resolution of 3 m $\times$ 3 m $\times$ 3 m was selected after preliminary analyses revealed negligible differences in radiation outputs at finer resolutions.

Meteorological boundary conditions for the simulations were derived from the Hong Kong Observatory (HKO), utilizing ENVI-met's Full Forcing Method with inputs including SW radiation, air temperature, relative humidity, and wind speed/direction (see Appendix B). To ensure the accuracy of LW flux calculations, simulations commenced 24 h prior to measurement periods, allowing surface temperatures and building materials to equilibrate. To compensate for the missing incoming LW radiation from HKO, three different methods were used to derive LW radiation: Method 1 used ENVI-met's internal calculation, Method 2 incorporated on-site LW measurements, and Method 3 employed a cloud-cover approximation method to refine the model inputs (see Section 2.4). Based on the architectural data, the window-to-façade ratio was estimated to be 30 % glass and 70 % concrete. This mixed-material approach was employed to simulate the reflective properties of windows without the need for full 3D modeling of individual windows and resulted in an average albedo of 0.365 for the combined wall material. The mixed-material walls, with a thickness of 30 cm, exhibit a SW radiation absorption of 36.5 %, reflect an equivalent percentage, and allow 27 % of the SW radiation to transmit. Emissivity is quantified at 0.9. It is simulated with a density of 2304 kgm^{-3} , a thermal conductivity of 1.435 $\text{Wm}^{-1}\text{K}^{-1}$, and a specific heat capacity of 820 $\text{Jkg}^{-1}\text{K}^{-1}$. Vegetation at the Natural Shading site was modeled using ENVI-met's Alber module, with crown dimensions calibrated to field surveys for accurate representation of the tree's structural complexity and its impact on shading and microclimatic conditions. The simulated large tree at this site features a Leaf Area Density (LAD) of 1.1 m^2m^{-3} and a Leaf Area Index (LAI) of 3.25 m^2m^{-2} over the measurement location, with the albedo of the leaves set to 0.18. The arboricultural parameters were measured in situ and corroborated with aerial imagery. Tree species were identified on-site and replicated with high fidelity within the model domain. Furthermore, photographic evidence was employed to incorporate hedgerows, grasslands, and shrubs into the model environment.

2.4. Simulation configurations

To assess the sensitivity of microclimate modeling to key parameters, three progressively refined simulation configurations were developed. These iterations primarily concentrated on the critical influence of SW radiation, with systematic adjustments to the albedo for outgoing SW radiation (SWout) and cloud cover for incoming SW radiation (SWin), underscoring the significance of these factors in attaining precise and reliable simulation outcomes.

Configuration 1 employed a conventional approach, estimating surface albedo using material properties sourced from the ENVI-met database. In the Open Space area, a light concrete pavement with an albedo of 0.5 was used, while the surface in the Artificial Shading area consisted of a used pavement with an albedo of 0.25. In Natural Shading, an unsealed soil was chosen to create a natural surface, with its albedo dynamically calculated by ENVI-met based on the current soil moisture content. Concurrently, LW radiation was internally calculated by ENVI-met due to the unavailability of LW forcing data from HKO. This method provided a baseline for comparison but introduced potential inaccuracies due to albedo assumptions and simplified LW flux estimations.

Configuration 2 introduced empirical albedo (α) calibration for the Open Space site using incoming and outgoing on-site SW radiation measurements, calculated with Eq. (3). The albedo calibration was undertaken to enhance accuracy, as Aleksandrowicz et al. (2023) [18] illustrated the advantages of using empirically measured albedo values. The default values in ENVI-met's standard materials database may not consistently correspond to the actual properties of specific materials, underscoring the necessity for precise calibration.

$$\alpha = \frac{SW_{out}}{SW_{in}} \quad (3)$$

The average albedo value across the three measurement days was determined to be 0.26 and was subsequently used to ensure consistency and accuracy in the simulations. This value was chosen as a balanced representation, considering the observed daily averages (July 29, 2022: Albedo 0.288; August 15, 2022: Albedo 0.283; August 23, 2022: Albedo 0.207) and the decision to avoid unnecessary complexity by not distinguishing albedo changes for each day, as the impact on the simulations was deemed insignificant. The albedo of the buildings remained the same during all simulations. This configuration also incorporated on-site LW radiation measurements to improve boundary conditions, effectively replacing the model's internally calculated values. By addressing the critical role of albedo and forcing LW radiation, this configuration aims to improve the accuracy of radiation flux simulations.

Configuration 3 refined LW and SW radiation inputs by approximating cloud cover dynamics through a streamlined two-step method. Initially, a baseline simulation without buildings or clouds was conducted at the study area's geographic coordinates. Subsequently, additional test simulations were performed, each incrementally increasing middle-layer cloud cover in 0.5/8 steps, up to a fully overcast condition (8/8), resulting in a total of 16 simulations. As the radiation sensors only recorded global SW radiation, but not its partitioning into direct and diffuse components, the simulation outputs enabled the derivation of cloud cover-specific partitioning ratios. These ratios were then applied to the measured incoming SW radiation values to estimate their direct and diffuse components. As the field measurements were taken near ground level and were thereby influenced by local obstructions (i. e., with a sky view factor (SVF) < 1), the data was extrapolated to a hypothetical SFV of 1. Afterwards, the resulting SVF-adjusted radiation values, now split into direct and diffuse components, served as forcing data at the model's upper boundary. The model area was simulated using the new forcing data and by comparing the simulation results with the measured values, the best-fitting cloud fraction was identified for each timestep (Appendix Fig. B16 – Fig. B18). During sunlit periods, direct radiation dominated, allowing clear-sky conditions to be assumed for peak irradiance intervals, while shaded intervals required iterative adjustments for diffuse radiation. The derived cloud fractions were used to compute LW radiation at the model's upper boundary, employing an empirical approach inspired by the works of Oke (1987) [8], Bolz (1949) [46] and Taesler and Andersson (1984) [47] as implemented by Bruse (2000) [48]. This method partitions cloud effects across atmospheric layers as described in Eqs. (4) to (6):

Table 2

Statistical Measures Across All Days for Measured Incoming Shortwave Radiation and Simulation Configurations.

Location	Simulation	Parameter	R ²	RMSE [Wm ⁻²]
Open Space	Config. 1	SWin	0.630	201.82
Natural Shading	Config. 1	SWin	0.804	21.07
Artificial Shading	Config. 1	SWin	0.445	18.55
Open Space	Config. 2	SWin	0.628	202.06
Natural Shading	Config. 2	SWin	0.793	21.15
Artificial Shading	Config. 2	SWin	0.431	16.64
Open Space	Config. 3	SWin	0.984	44.29
Natural Shading	Config. 3	SWin	0.781	17.91
Artificial Shading	Config. 3	SWin	0.193	14.71

$$L^{\downarrow,0} = \sigma \cdot T_{2m}^4 \left[1 - 0.261 \cdot e^{-7.77 \cdot 10^{-4} (273 - T_{2m})^2} \right] \quad (4)$$

$$L^{\downarrow,0}(clouds) = L^{\downarrow,0} \cdot \left(1 + \omega_{sum} \cdot \left(\frac{N_{sum}}{8} \right)^2 \right) \quad (5)$$

Here, $L^{\downarrow,0}$ represents the downward LW radiation at the model's upper boundary, while $L^{\downarrow,0}(clouds)$ indicates the same under cloud cover. The Stefan-Boltzmann constant is denoted by σ , and T_{2m} is the air temperature measured at 2 m above ground level.

$$\omega_{sum} = \frac{0.22 \cdot N_l + 0.185 \cdot N_m + 0.06 \cdot N_h}{N_{sum}} \quad (6)$$

The parameter ω_{sum} quantifies the average impact of cloud cover on LW radiation where N_{sum} is the total cloud cover in eighths, and N_l , N_m

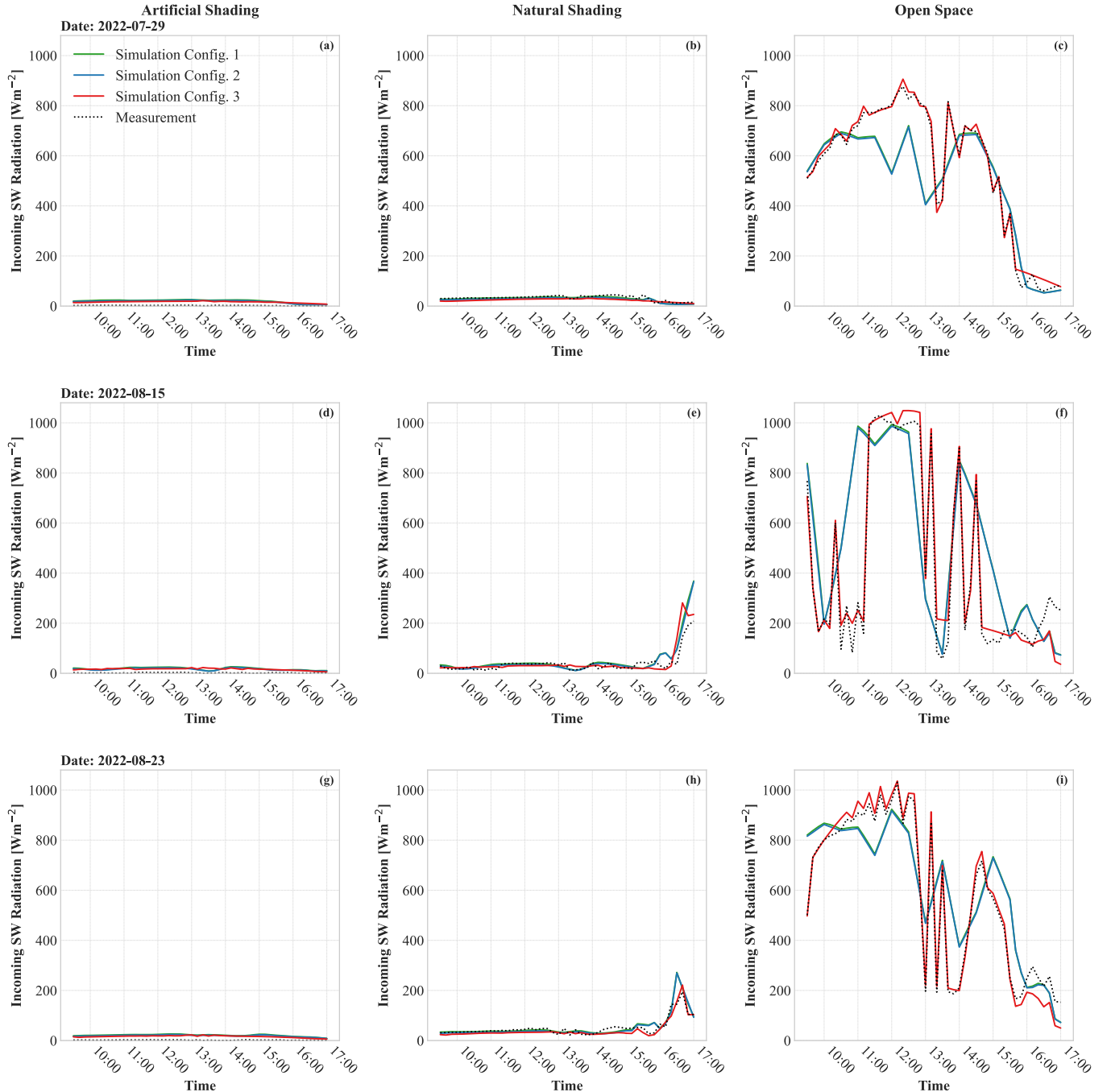


Fig 3. Comparison of Incoming Shortwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

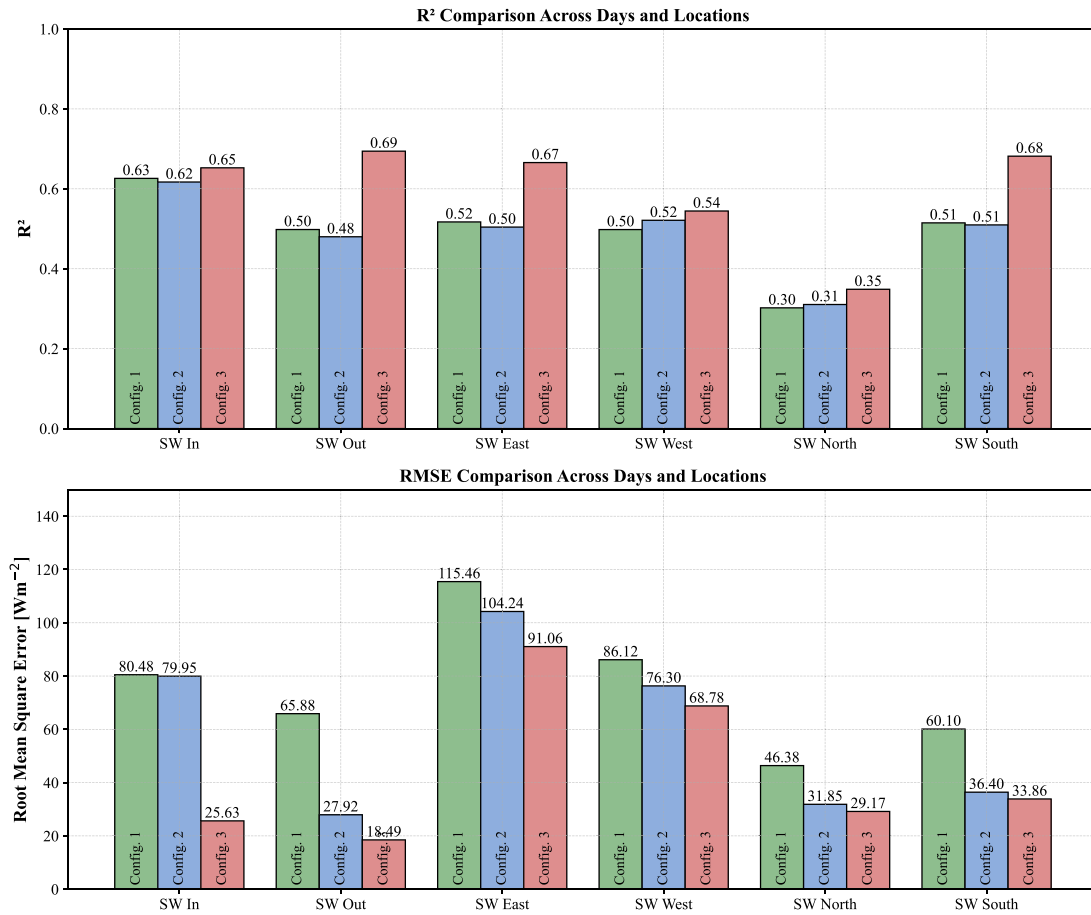


Fig 4. Presentation of R^2 and RMSE for Shortwave Radiation Fluxes Across Six Directions, Averaged Over All Days and Locations.

and N_h specify the coverage of low, medium and high clouds, respectively [48,49].

Hourly cloud cover data in percentage was obtained from a nearby weather station (HKO Station). While this data provides valuable insights, there are some challenges in directly comparing it to the approximated clouds. The weather station data is recorded at a broader temporal resolution, and the gradation between possible values might be too coarse for this specific application, as certain value levels appear frequently. In addition to the complex cloud cover conditions in subtropical sites, the station's location, 1.3 km away from the measurement site, introduces further constraints in making direct comparisons. Despite these limitations, the general trends in cloud cover align with the approximated middle-layer clouds.

In ENVI-met, the sky is modeled with a uniform cloud cover in all directions, which differs from reality where cloud distribution can vary significantly. Even minimal cloud cover, such as 1/8, can cause substantial shadowing if positioned directly in front of the sun. Unfortunately, the specific positions of clouds cannot be determined from the weather station data, limiting the scope for detailed comparisons. Nonetheless, this approach helped minimize radiative flux discontinuities and incorporated site-specific cloud dynamics that are not captured in the station data. While it estimated only middle-layer clouds, setting low and high clouds to zero, it provides a solid baseline for future refinements.

2.5. Validation metrics

The validation of simulation results was conducted through a statistical comparison with measured field data, utilizing key evaluation metrics such as root mean square error (RMSE) and the coefficient of

determination (R^2). RMSE provides a measure of error magnitude, expressed in Wm^{-2} for radiative fluxes and in Kelvin for MRT, offering a clear indication of the model's accuracy across different variables. The R^2 value offers insights into the proportion of variance explained by the model, consistently ranging from 0 to 1. To visually convey modeling performance, regression scatter plots are employed, highlighting the relationship between simulated and observed MRT values and their associated radiative fluxes. These scatter plots provide an intuitive understanding of the model's performance across different measurement sites and simulation configurations. Additionally, bar plots present the aggregated statistical metrics across different measurement sites and simulation configurations.

3. Results

The results are structured according to the sequential dependency of radiative components in the modeling process. The analysis begins with SW radiation, as it is a critical determinant of accuracy for subsequent parameters. Small variations in SW radiation can significantly affect other model outputs. Once SW radiation is accurately captured, the focus shifts to LW radiation, which is essential for understanding surface and atmospheric radiative interactions. Finally, the MRT is examined, integrating both SW and LW radiation from six directions. The precision of MRT relies on the accurate modeling of these radiative components, making it the culmination of the result analysis. Each subsection presents quantitative findings, supported by statistical metrics as well as visual comparisons to measurement data. A detailed comparison of SW and LW radiation fluxes – separated into six directions and shown for all simulation configurations alongside measurement data – can be found in [Appendix A](#).

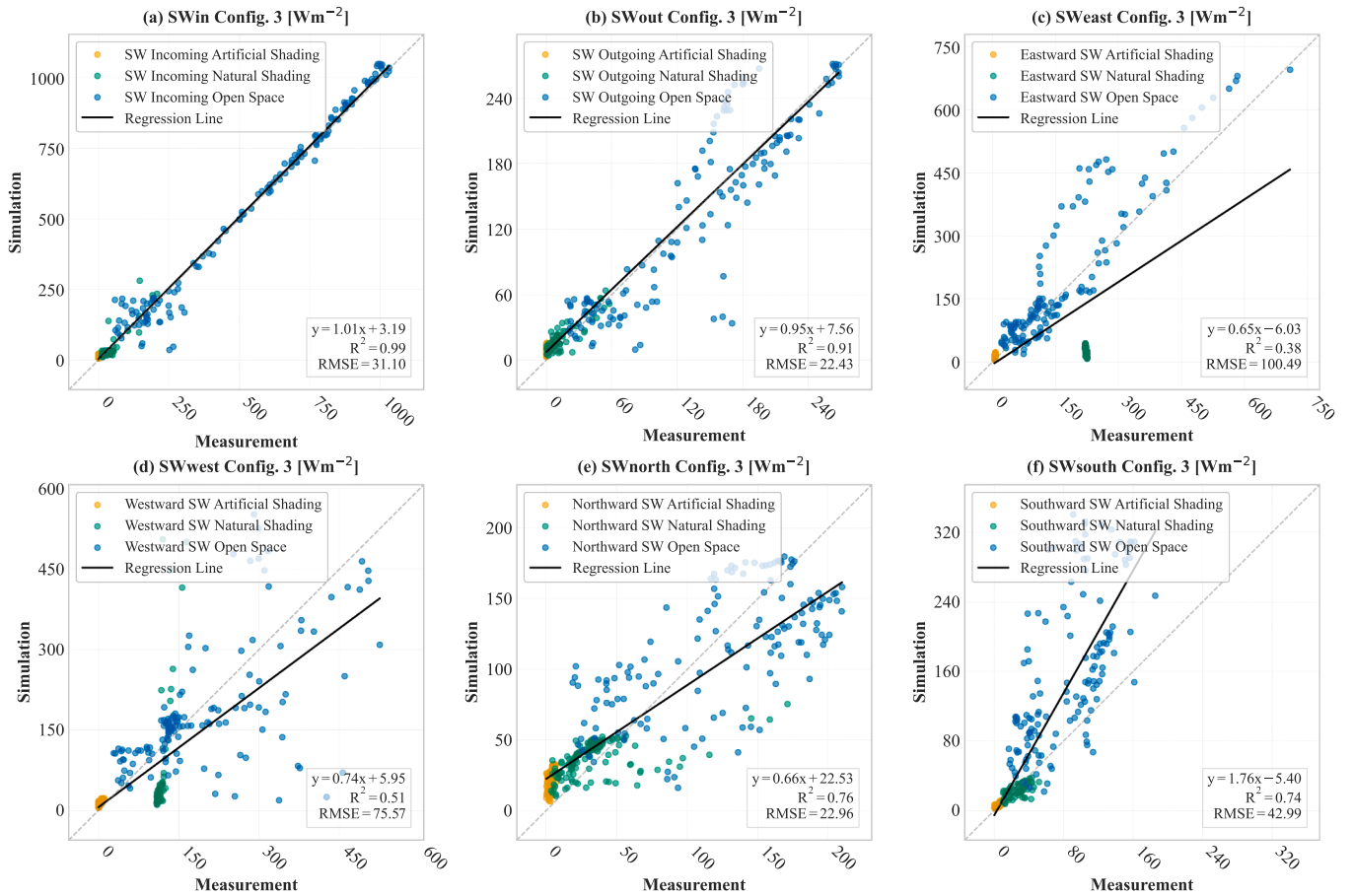


Fig 5. Scatter Plots of Linear Regression Between Measured and Simulated Shortwave Radiation Across Six Directions for All Three Measurement Days.

Table 3

Statistical Measures Across All Days for Measured Outgoing Longwave Radiation and Simulation Configurations.

Location	Simulation	Parameter	R^2	RMSE [Wm^{-2}]
Open Space	Config. 1	LWout	0.806	36.82
Natural Shading	Config. 1	LWout	0.866	17.13
Artificial Shading	Config. 1	LWout	0.920	6.93
Open Space	Config. 2	LWout	0.790	19.24
Natural Shading	Config. 2	LWout	0.870	21.79
Artificial Shading	Config. 2	LWout	0.930	7.32
Open Space	Config. 3	LWout	0.887	14.86
Natural Shading	Config. 3	LWout	0.875	18.91
Artificial Shading	Config. 3	LWout	0.927	5.86

3.1. Shortwave radiation fluxes

Progressive refinement of the simulation configurations yielded substantial improvements in SW radiation predictions across all directions. In the Open Space scenario, characterized by direct solar exposure, the RMSE for incoming SW radiation decreased from 201.82 Wm^{-2} in configuration 1 to 44.29 Wm^{-2} in configuration 3, accompanied by a near-perfect coefficient of determination ($R^2 = 0.984$; Table 2). Regarding the incoming SW radiation, the Natural Shading scenario exhibited lower errors ($\text{RMSE} = 17.91 \text{ Wm}^{-2}$, $R^2 = 0.781$), while Artificial Shading showed the lowest RMSE (14.71 Wm^{-2}) but poor correlation ($R^2 = 0.193$), likely due to frequent negative SW values caused by calibration drift or sensor misalignment, which necessitated adjusting all values to preserve diurnal trends and ensure reliable evaluation.

The critical role of cloud approximation is evident in Fig. 3, where Config. 3 successfully replicated transient irradiance spikes caused by

passing clouds in the Open Space scenario. Directional analysis (Fig. 4) revealed systematic improvements across all orientations. The northern direction achieved the lowest RMSE (29.17 Wm^{-2} in Config. 3) compared to the other cardinal directions, while the eastern direction showed the largest deviations ($\text{RMSE} = 91.06 \text{ Wm}^{-2}$), with morning radiation values (9:00–13:00) consistently overestimated. Post-13:00 alignment with measurements suggests unresolved reflection effects tied to model resolution limits (Appendix Fig. A3).

Albedo calibration in Config. 2 reduced outgoing SW radiation (SWout) errors by 62 % in Open Space (RMSE : 158.41 Wm^{-2} to 59.52 Wm^{-2} ; Appendix Fig. A1; Appendix Fig. A11). Averaged across all six directions, SW radiation RMSE decreased by 23 % from Config. 1 (14.98 Wm^{-2}) to Config. 3 (11.58 Wm^{-2}). Excluding Artificial Shading data ($R^2 = 0.43$), correlations surged to 0.882 (SWin) and 0.847 (SWout), emphasizing the model's proficiency in unobstructed environments. Scatterplots in Fig. 5 further validate these improvements, showing near-ideal regression slopes for SWin and SWout in Config. 3.

Overall, improvements in simulation configurations consistently enhanced RMSE across all directions. Similarly, R^2 values showed improvements with outgoing SW radiation and SW radiation received from the south exhibiting the highest averaged correlation values of 0.69 and 0.68, respectively.

3.2. Longwave radiation fluxes

Diurnal LW radiation simulations demonstrated robust performance across all configurations, with marginal iterative improvements. Outgoing LW radiation (LWout) in Open Space achieved an RMSE of 14.86 Wm^{-2} ($R^2 = 0.887$) in Config. 3 (Table 3), while Natural Shading showed the largest deviation ($\text{RMSE} = 18.91 \text{ Wm}^{-2}$; $R^2 = 0.875$). Artificial

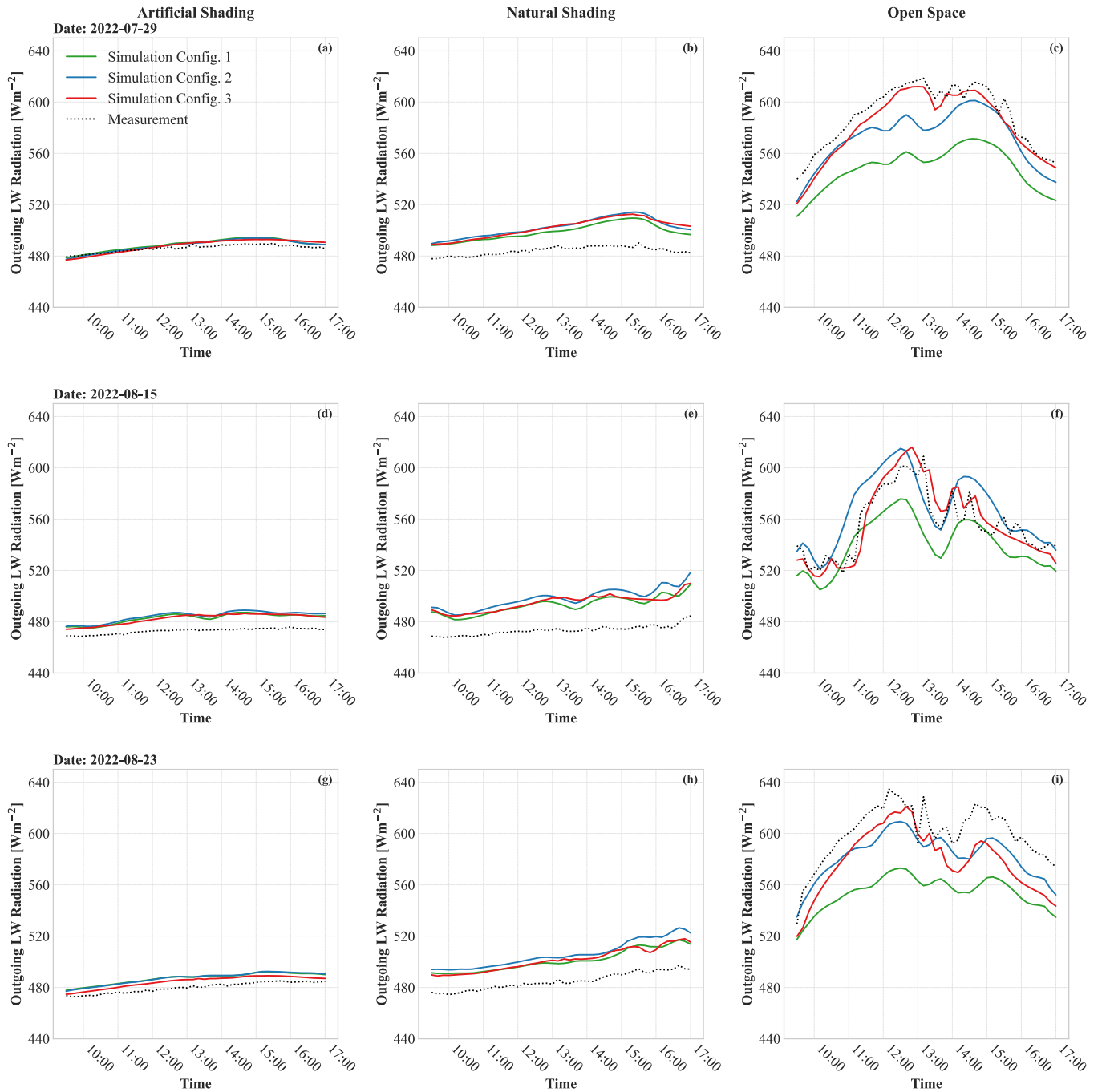


Fig. 6. Comparison of Outgoing Longwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

Shading exhibited the highest accuracy ($\text{RMSE} = 5.86 \text{ Wm}^{-2}$; $R^2 = 0.927$), likely due to reduced sky view factors.

Directional LW fluxes (Figs. 6–8) showed strong agreement, with RMSE consistently below 21 Wm^{-2} . While the cloud approximation and albedo modification contributed to the estimation accuracy of LW radiation fluxes, their overall impact was limited. This is demonstrated by the fact that even Config. 1, which lacked specific LW forcing, yielded reliable results (Fig. 6). In the shaded locations, LW radiation in all simulation configurations slightly exceeds the measured values. In contrast, at the unshaded location, the results of the first two simulation configurations were generally lower than the measured values (Fig. 6).

The linear regression slopes in Fig. 8 align closely with the ideal linear regression line, particularly for northern-direction LW radiation. However, slight R^2 reductions (~ 0.02 – 0.04) in later configurations for

Open Space and Natural Shading leading to a slight decrease in R^2 in Config. 3 (Fig. 7) suggest potential overfitting of cloud dynamics or unresolved heat retention from adjacent structures. The RMSE values, averaged across the three measurement days and locations, differed by no more than 7 Wm^{-2} between the three simulation configurations.

3.3. Mean radiant temperature

Diurnal MRT simulations improved progressively across configurations, with Open Space RMSE decreasing from 10.17 K (Config. 1) to 5.07 K (Config. 3; $R^2 = 0.760$; Table 4). Natural Shading achieved the closest alignment ($\text{RMSE} = 1.51 \text{ K}$; $R^2 = 0.771$), while Artificial Shading showed minimal absolute error ($\text{RMSE} = 1.27 \text{ K}$) despite lower correlation ($R^2 = 0.666$).

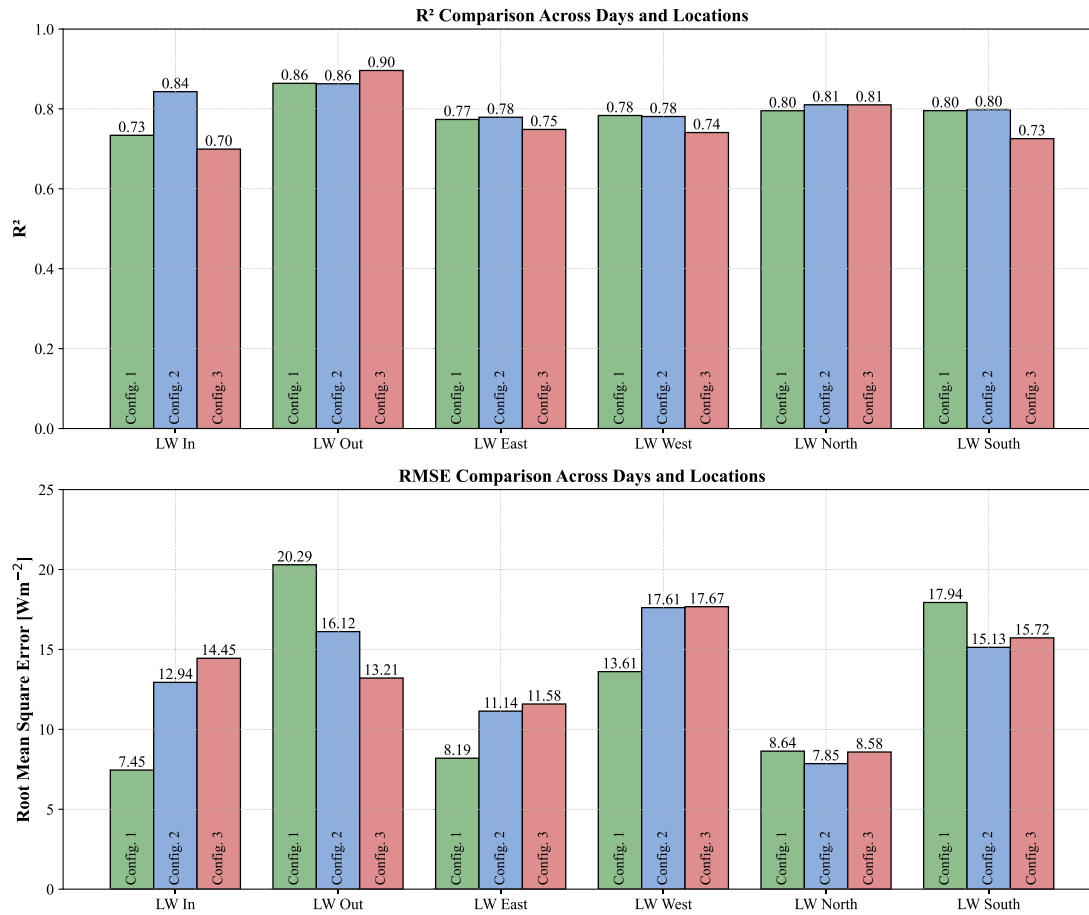


Fig 7. Presentation of R² and RMSE for Longwave Radiation Fluxes Across Six Directions, Averaged Over All Days and Locations.

Systematic MRT overestimations in Open Space (Fig. 9) were mitigated by albedo calibration, which corrected an initially overestimated concrete pavement albedo (0.5 to 0.26), reducing errors by up to 3 K.

Averaged across all scenarios, RMSE of MRT showed 2.62 K in Config. 3 (Fig. 10), with R² peaking at 0.73. This represents a low deviation for a sensitive parameter like MRT, which integrates both SW and LW radiation from six different directions.

Fig. 11 illustrates a strong linear regression; however, residual deviations at higher MRT values underscore ongoing challenges in accurately modeling extreme radiative loads.

4. Discussion

The results indicate that ENVI-met performs robustly in modeling key diurnal radiative parameters across diverse urban microclimates closely aligning with field measurements. The improved MRT calculation, previously evaluated by Sinsel et al. (2022) [26] in another location in Hong Kong, also performs well in this study area. This discussion contextualizes these results, evaluates their implications for urban climate modeling and identifies pathways to further enhance simulation accuracy.

4.1. Model performance

The experimental cloud approximation method, combined with albedo calibration and applied to high temporal resolution data, proved effective in resolving the fluctuating patterns of SW radiation typically caused by passing clouds or changing atmospheric conditions, despite the absence of direct on-site cloud measurements. This approach reduced Open Space SWin RMSE by 78 % (from 201.82 to 44.29 Wm⁻²;

Table 2), validating its utility for studies lacking dedicated cloud monitoring. However, directional discrepancies in eastern SW fluxes (Fig. 4) suggest unresolved reflection effects, likely due to the 3 m grid resolution's limited capacity to capture small-scale features (e.g. transient reflections from windows, playground equipment, or textured surfaces). While small algorithmic errors can be another possible source for these discrepancies, they may also result from general model uncertainties, as it is impossible to perfectly represent all aspects in a model due to parameterization limitations.

The divergent performance between SW and LW radiation highlights distinct modeling requirements. While SW fluxes demanded iterative adjustments (cloud approximation, albedo calibration), diurnal LW radiation modeling remained relatively stable across configurations, with RMSE consistently below 21 Wm⁻² (Fig. 7). The high LWout correlations (R² = 0.887 in Open Space) confirm ENVI-met's robust handling of surface emissivity for common urban materials. Notably, Aleksandrowicz et al. (2023) [18] emphasized the necessity of empirical material calibration for SW radiation accuracy – a principle corroborated here, as albedo adjustments reduced SWout errors by 62 % (Appendix Fig. A11).

4.2. Implications for MRT

Contrary to earlier studies reporting MRT underestimations in shaded areas [18,29], the results show no systematic shading-related underestimations. Instead, the findings do indicate a tendency for diurnal MRT to be overestimated in unshaded areas. This indicates that the underestimations in unshaded areas, previously identified by Gál and Kantor (2020) [50] in older ENVI-met versions, appear to be mitigated in the context of this case study. Reducing the concrete pavement

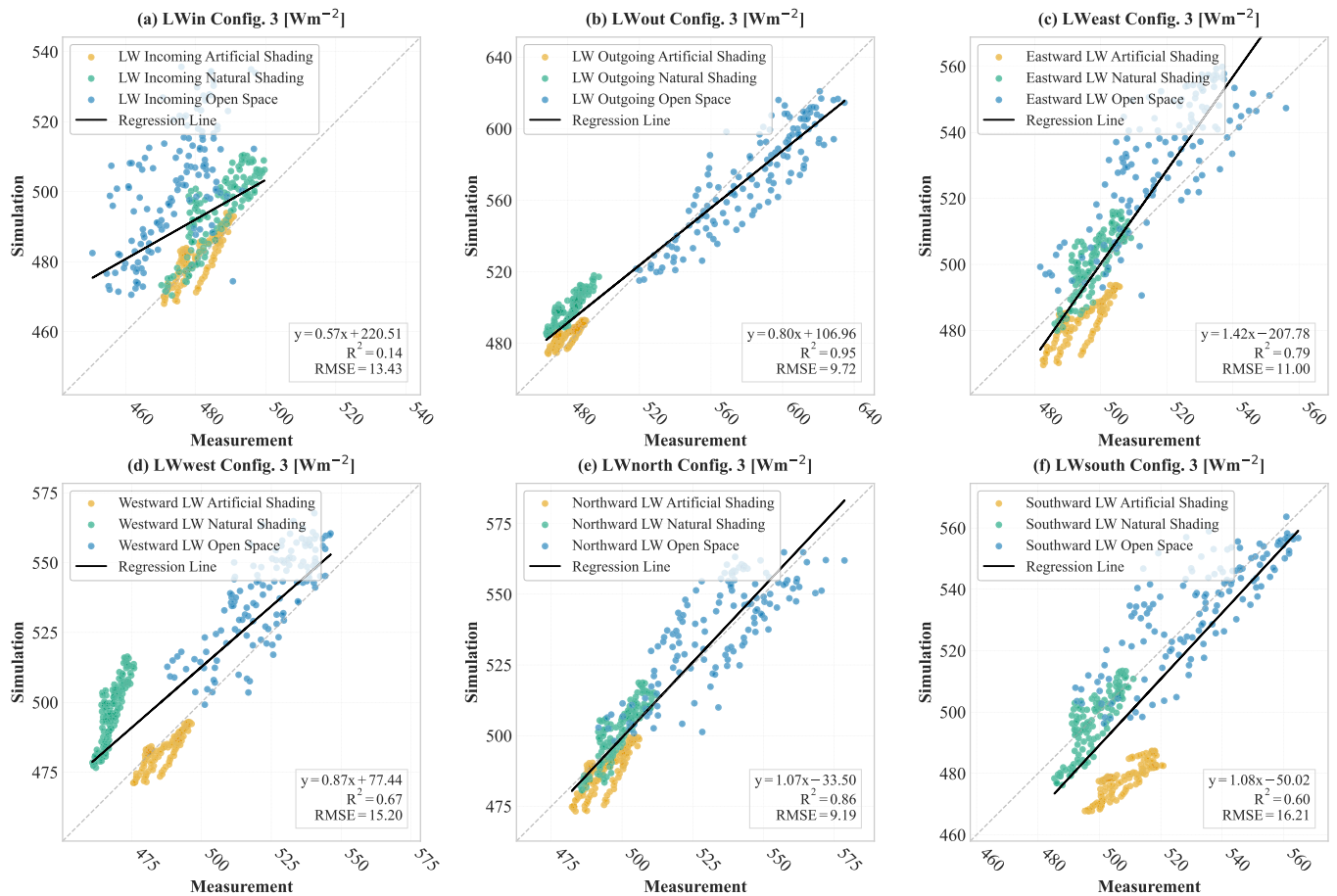


Fig. 8. Scatter Plots of Linear Regression Between Measured and Simulated Longwave Radiation Across Six Directions for All Three Measurement Days.

Table 4

Statistical Measures Across All Days for Measured MRT and Simulation Configurations.

Location	Simulation	Parameter	R^2	RMSE [K]
Open Space	Config. 1	MRT	0.475	10.17
Natural Shading	Config. 1	MRT	0.756	2.69
Artificial Shading	Config. 1	MRT	0.549	0.94
Open Space	Config. 2	MRT	0.466	7.34
Natural Shading	Config. 2	MRT	0.777	2.16
Artificial Shading	Config. 2	MRT	0.645	0.98
Open Space	Config. 3	MRT	0.760	5.07
Natural Shading	Config. 3	MRT	0.771	1.51
Artificial Shading	Config. 3	MRT	0.666	1.27

albedo to 0.26 directly addressed overestimations, lowering Open Space diurnal MRT errors by 3 K. This adjustment corroborates the assertion that standard ENVI-met material databases sometimes misrepresent real-world albedo values, necessitating site-specific calibration, as previously demonstrated by Ouyang et al. (2022) [51], where localized materials yielded the best results.

The strong agreement between simulated and measured MRT across all shading scenarios (RMSE = 1.27 – 5.07 K; Table 4) underscores ENVI-met's capability to accurately resolve spatially variable diurnal radiative fluxes. These results are comparable to those of Sinsal et al. (2022) [26] in Hong Kong, reporting RMSE values of 4.23 K for unshaded locations and 1.65 K for shaded scenarios. Despite employing a coarser spatial resolution of 3 m and incorporating data over three days and thereby introducing greater variability, the findings demonstrate the robustness of the cloud approximation and albedo calibration methods used. Aleksandrowicz et al. (2023) [18] conducted a study in Tel Aviv-Yafo,

Israel, which used on-site albedo calibration and a 1 m grid resolution but reported higher RMSE values of 13.32 K for unshaded areas and 6.08 K for shaded locations. Their reliance on full forcing data from a central measuring station, spatially distant from most measurement sites, may have contributed to these results. Similarly, Alzahrani and Gadi's (2024) [27] study in Mecca City, Saudi Arabia, which did not utilize on-site albedo measurements, yielded RMSE values of 7.05 K in winter and 4.73 K in summer for unshaded areas. Xiao et al.'s (2025) [29] study in Guangzhou, China, using forcing data from a station 1 km away, reported RMSE values of 5.86 K for unshaded areas and 2.46 K for tree-shaded areas.

By leveraging the methodologies of albedo calibration and cloud approximation, this study provides valuable insights for enhancing simulation accuracy, particularly where environmental variability or measurement distance may affect results. The good agreement between simulated and measured diurnal MRT values across the three distinct shading scenarios in the complex model area suggests that future research can extend beyond MRT observations at specific measurement sites. ENVI-met facilitates the evaluation of MRT across the entire model area, thereby broadening the scope of analysis (Fig. 12).

4.3. Future directions and practical considerations

Three key areas warrant further investigation to enhance the findings and advance the field. Firstly, cloud dynamics: While approximating middle-layer clouds sufficed for SWin alignment (Fig. 3), incorporating multi-layer cloud data being resolved in finer steps (low, medium, high) could refine diffuse radiation partitioning and further reduce MRT residuals. Automating the labor-intensive process of determining cloud cover through machine learning, artificial intelligence (AI), or data-

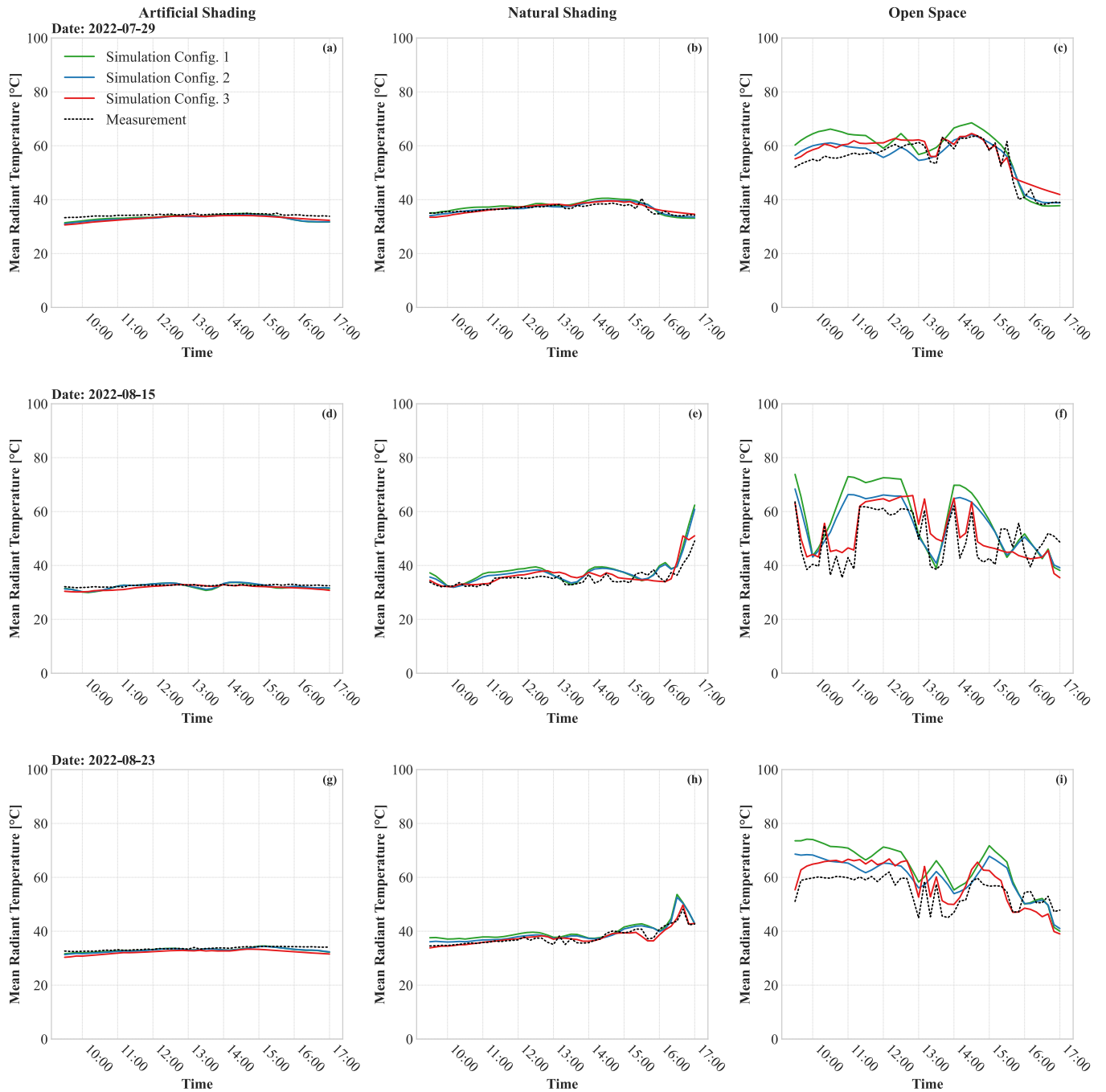


Fig 9. Comparison of MRT Across Different Configurations and Measurement Data.

finding algorithms could improve accuracy and reduce time investment. Future research should also focus on developing methods to approximate not only middle-layer clouds but also low and high clouds, which could potentially enhance SW and LW simulation results even when measurement data is incomplete.

Secondly, reflection modeling: Residual SW deviations in complex geometries (e.g., eastern direction in Fig. 4) underscore the challenges of simulating multi-reflective interactions at a 3 m resolution. Higher-resolution grids (<1 m) may better resolve reflections from small-scale objects (e.g., benches, signage) that vary with solar angle, although this would significantly increase computational model area preparation efforts.

Lastly, input data quality: The results reaffirm that ENVI-met's outputs depend critically on the accuracy of inputs, particularly albedo

calibration. While the model's internal algorithms perform well (e.g., LW radiation stability across configurations), users must prioritize empirical calibration of material properties to avoid systematic biases. Investigating diurnal variations in albedo and its representation in ENVI-met, along with simulating weather-dependent variability, could further refine model accuracy. To achieve this, expanding ENVI-met's material libraries to incorporate a broader range of surface properties could be beneficial for enhancing SW accuracy in heterogeneous urban environments. Complementary long-term albedo measurements would provide the empirical data necessary for adequate calibration, ensuring that the model accurately reflects real-world conditions. Additionally, measuring radiative fluxes in all six directions overnight would provide valuable data to validate ENVI-met's LW and thereby MRT modeling during nighttime conditions, enhancing the model's reliability in

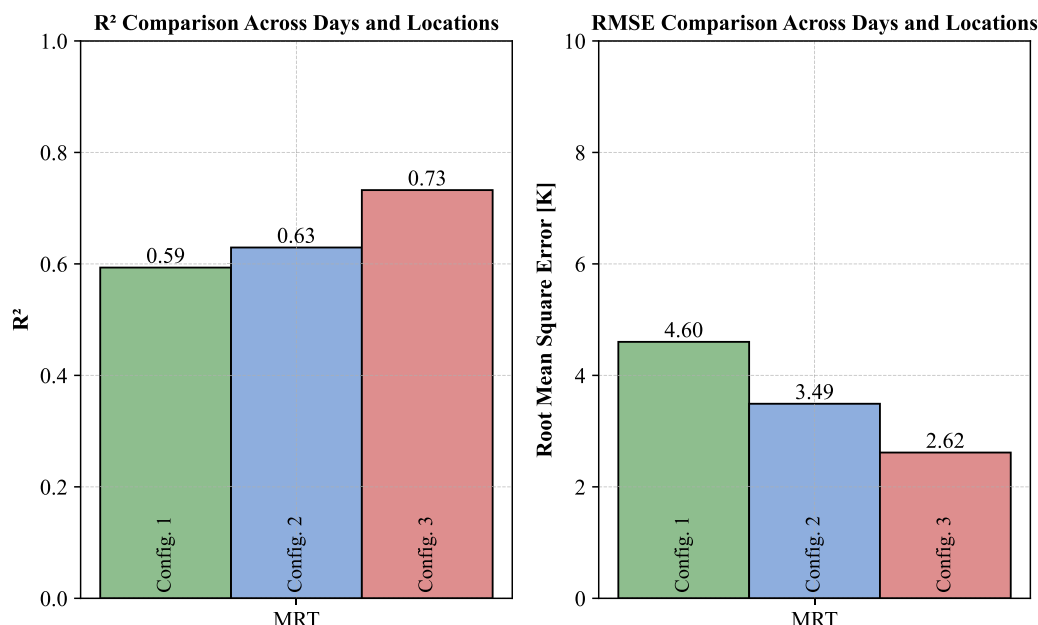


Fig 10. Presentation of R² and RMSE for MRT, Averaged Over All Days and Locations.

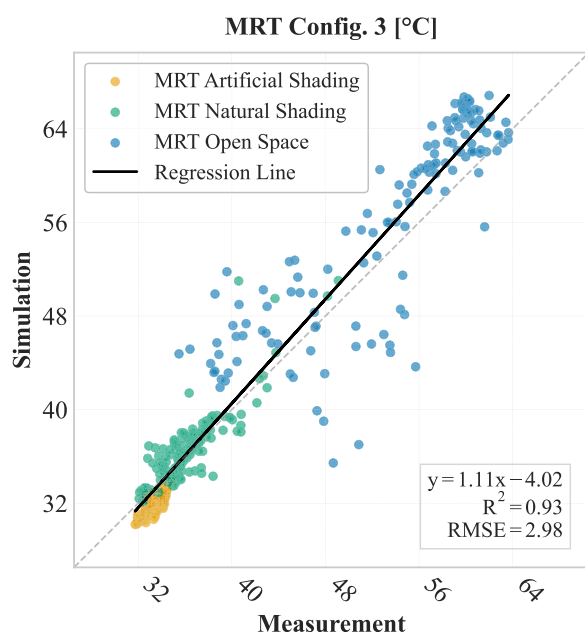


Fig 11. Scatter Plots of Linear Regression Between Measured and Simulated MRT Across Six Directions for All Three Measurement Days.

simulating nocturnal cooling processes critical for urban thermal comfort assessments.

5. Conclusion

The study evaluated ENVI-met's performance in simulating SW and LW radiative fluxes across six-directional components in three distinct urban environments in Hong Kong during the day: an unshaded plaza (Open Space), a tree-shaded area (Natural Shading), and a semi-enclosed building corridor (Artificial Shading). The results indicate that the accurate preparation of input data, such as empirical albedo calibration and cloud cover approximation, significantly enhances model performance.

For instance, in the Open Space scenario, iterative refinements

reduced RMSE for incoming SW radiation from 201.82 Wm⁻² in Config. 1 to 44.29 Wm⁻² in Config. 3, with a high coefficient of determination achieved for SW and LW fluxes. Configuration 1 employed a conventional approach, using ENVI-met's default material properties for albedo estimation and internally calculated LW radiation due to the lack of specific LW forcing data. This provided a baseline for comparison. In contrast, Configuration 3 refined both LW and SW radiation inputs by approximating cloud cover dynamics and employing empirical albedo calibration, demonstrating the substantial impact of these refinements on model accuracy.

Documenting cloud cover during data collection is advisable, as it can significantly enhance the accuracy of radiative flux forcing and facilitate the separation of SW measurement data into direct and diffuse components. The strong agreement between simulated and measured MRT across two shading scenarios (RMSE = 1.27 – 5.07 K) confirms ENVI-met's utility for modeling MRT in complex urban environments with both natural elements and artificial materials. The minimal LW deviations (<21 Wm⁻² RMSE) and strong MRT correlations across locations and days (R² = 0.73) validate its algorithms' underlying physics.

While ENVI-met's algorithms perform robustly under empirical constraints, input quality remains critical. This study validates its applicability in subtropical cities but calls for broader validation across diverse climates to generalize findings. By prioritizing input calibration and cloud dynamics refinement, future work can further advance urban microclimate modeling precision.

Fundings

This research is supported by Theme-based Research Scheme (No. T22-504/21-R) from the Research Grants Council (RGC) of Hong Kong.

CRedit authorship contribution statement

Peer Schöneberger: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tim Sinsel:** Writing – review & editing, Validation, Software, Project administration, Methodology, Conceptualization. **Wanlu Ouyang:** Writing – review & editing, Validation, Resources, Data curation. **Zheng Tan:** Writing – review & editing, Validation, Resources, Data curation. **Michael Bruse:** Writing – review & editing, Resources, Project administration. **Helge**

Spatial Distribution of MRT Values over Oi Man Estate,
Hong Kong on August 15, 2022, at 13:00

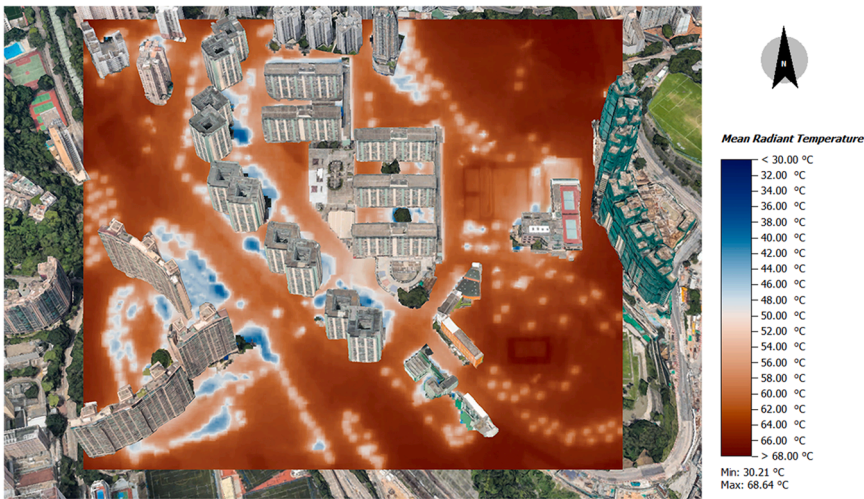


Fig 12. Illustration of Simulation Results for MRT on August 15, 2022, at 13:00 at a Height of 1.5 m Across the Entire Model Area.

Simon: Writing – review & editing, Validation, Software, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wanlu Ouyang reports financial support was provided by Research Grants Council Hong Kong. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Simulation and Measurement Results

[Fig A1](#), [Fig A2](#), [Fig A3](#), [Fig A4](#), [Fig A5](#), [Fig A6](#), [Fig A7](#), [Fig A8](#), [Fig A9](#), [Fig A10](#), [Fig A11](#), [Fig A12](#), [Fig A13](#), [Fig A14](#), [Fig A15](#), [Fig A16](#), [Fig A17](#), [Fig A18](#), [Fig A19](#)

Acknowledgements

Special thanks go to the Hong Kong Housing Authority for granting approval for our measurement in two estates. We would like to express our appreciation to Mr. Max Lee, Ms. Doris Tam, and Ms. Sze Wai Wong for their support and help project logistics. We also appreciate the assistance from Ms. Alexis Wang and Ms. Nancy Yi during the measurement.

Data availability

Data will be made available on request.

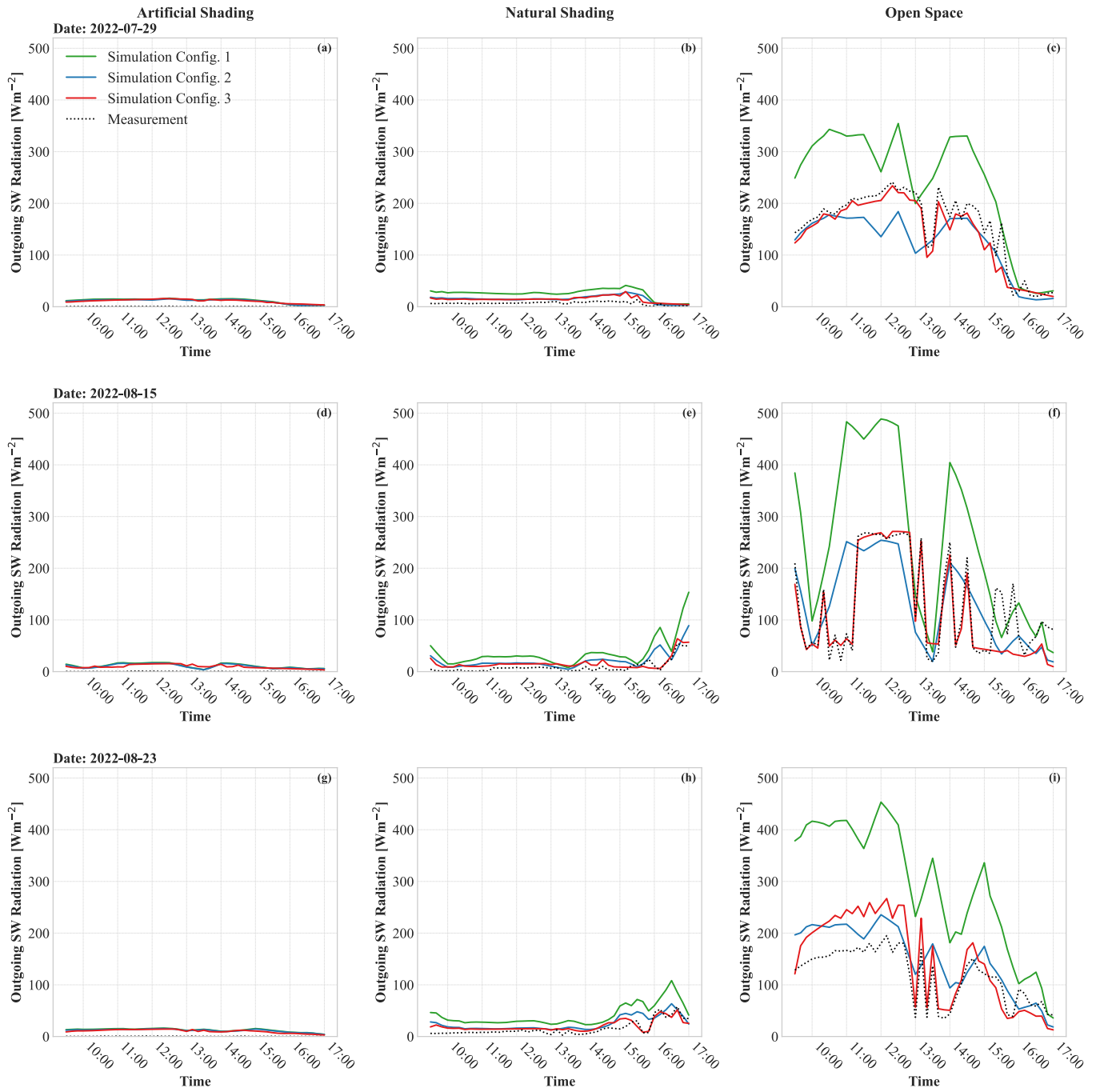


Fig A1. Comparison of Outgoing Shortwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

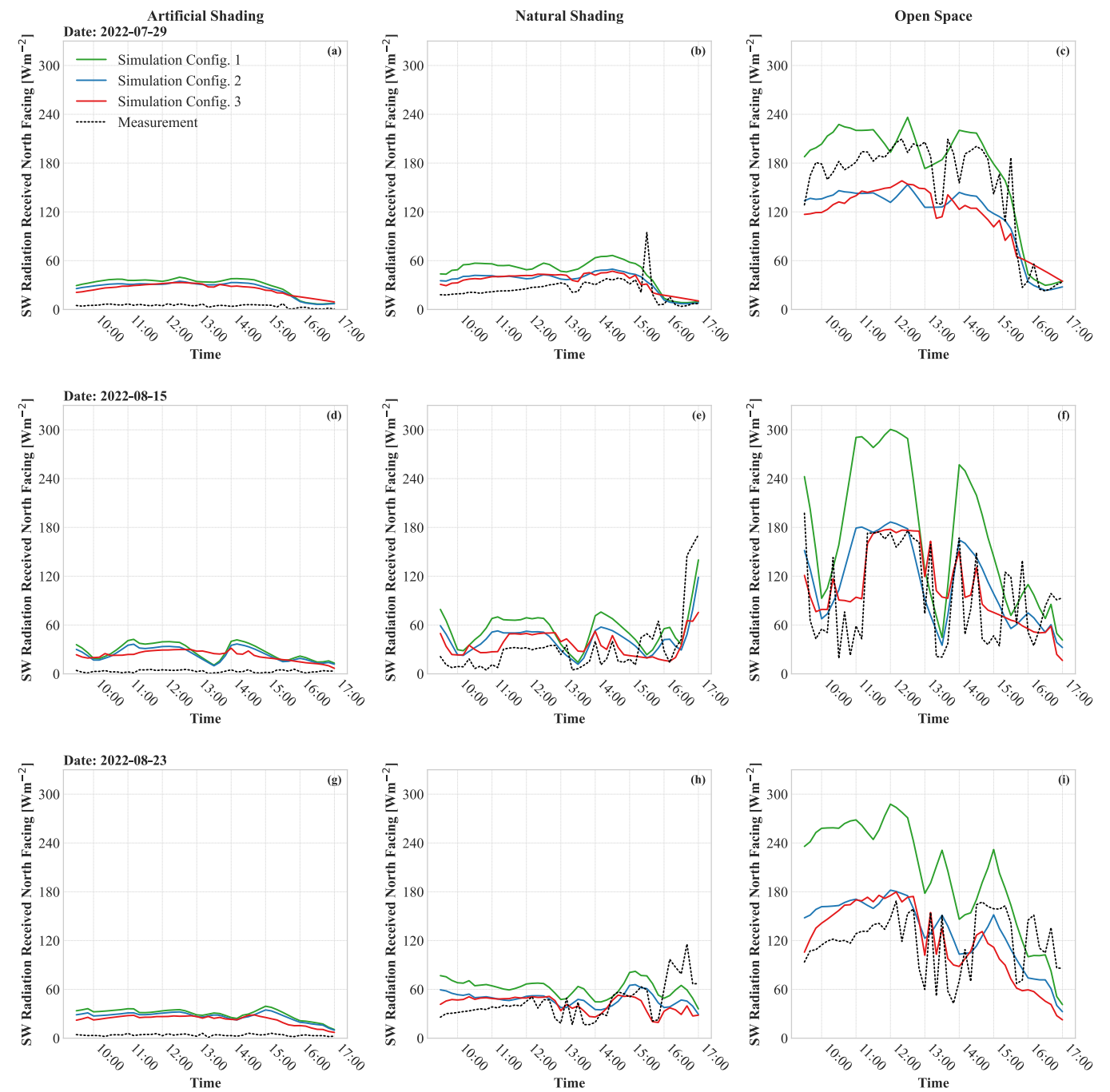


Fig A2. Comparison of Northward Shortwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

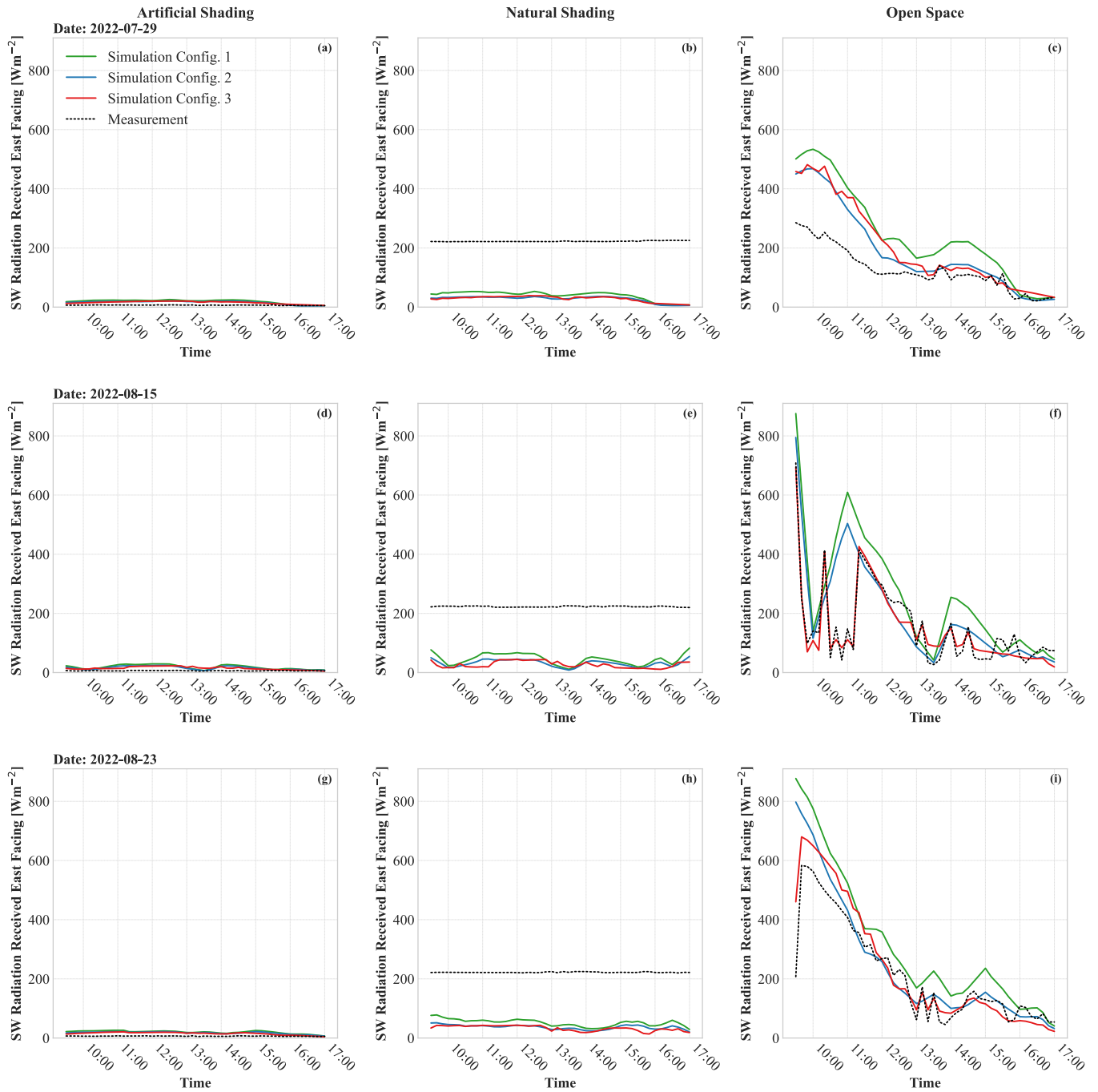


Fig A3. Comparison of Eastward Shortwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

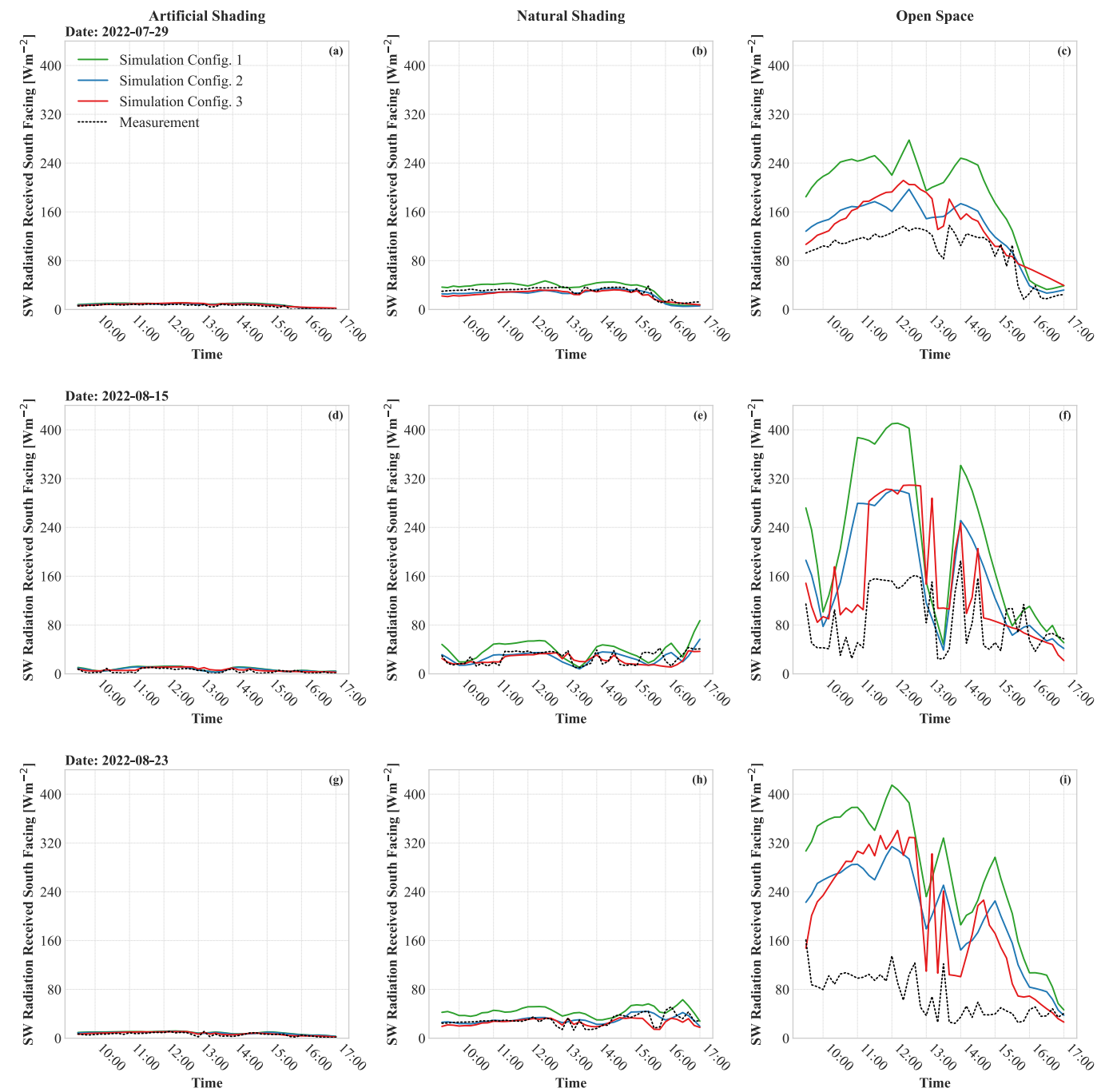


Fig A4. Comparison of Southward Shortwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

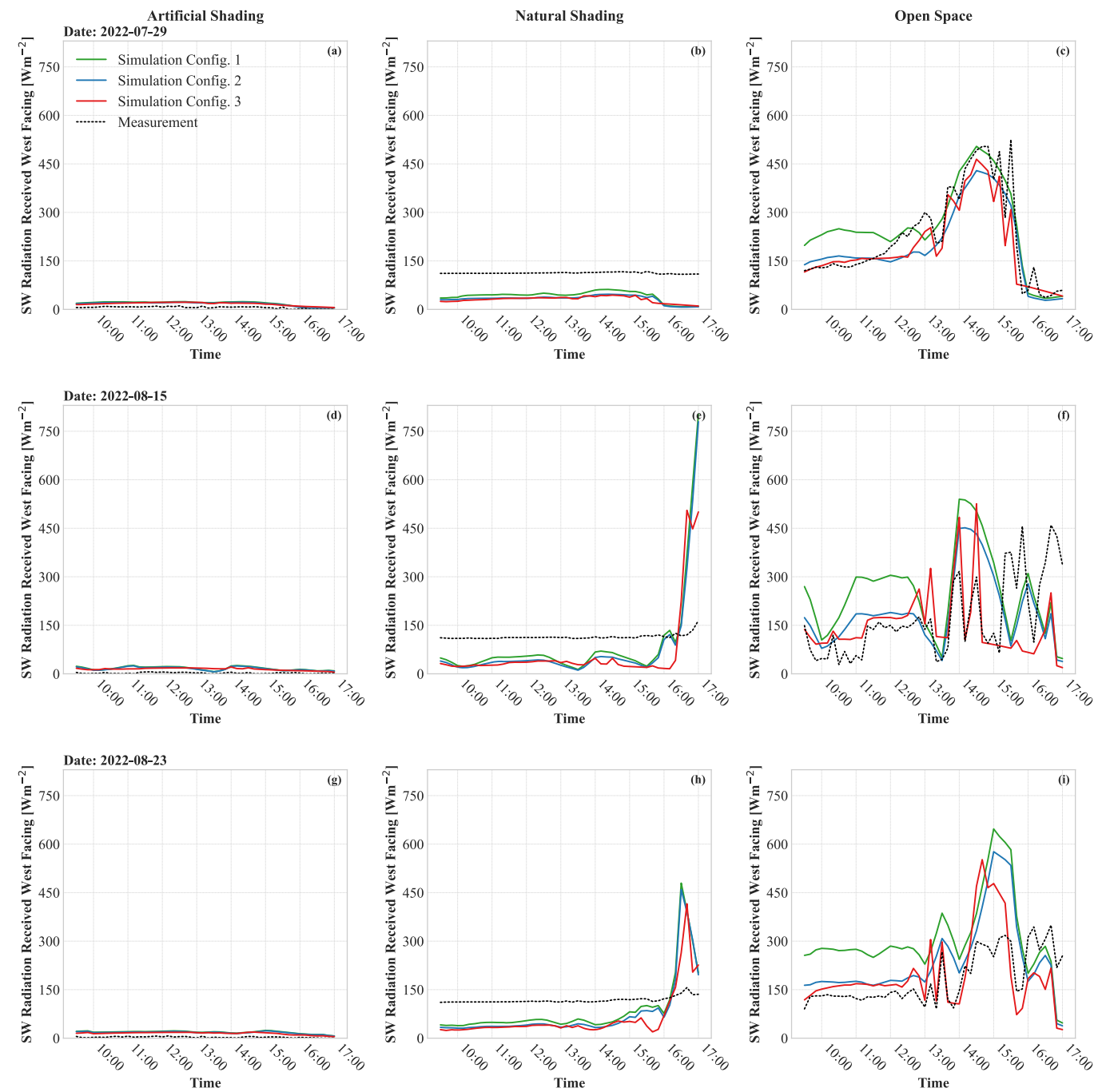


Fig A5. Comparison of Westward Shortwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

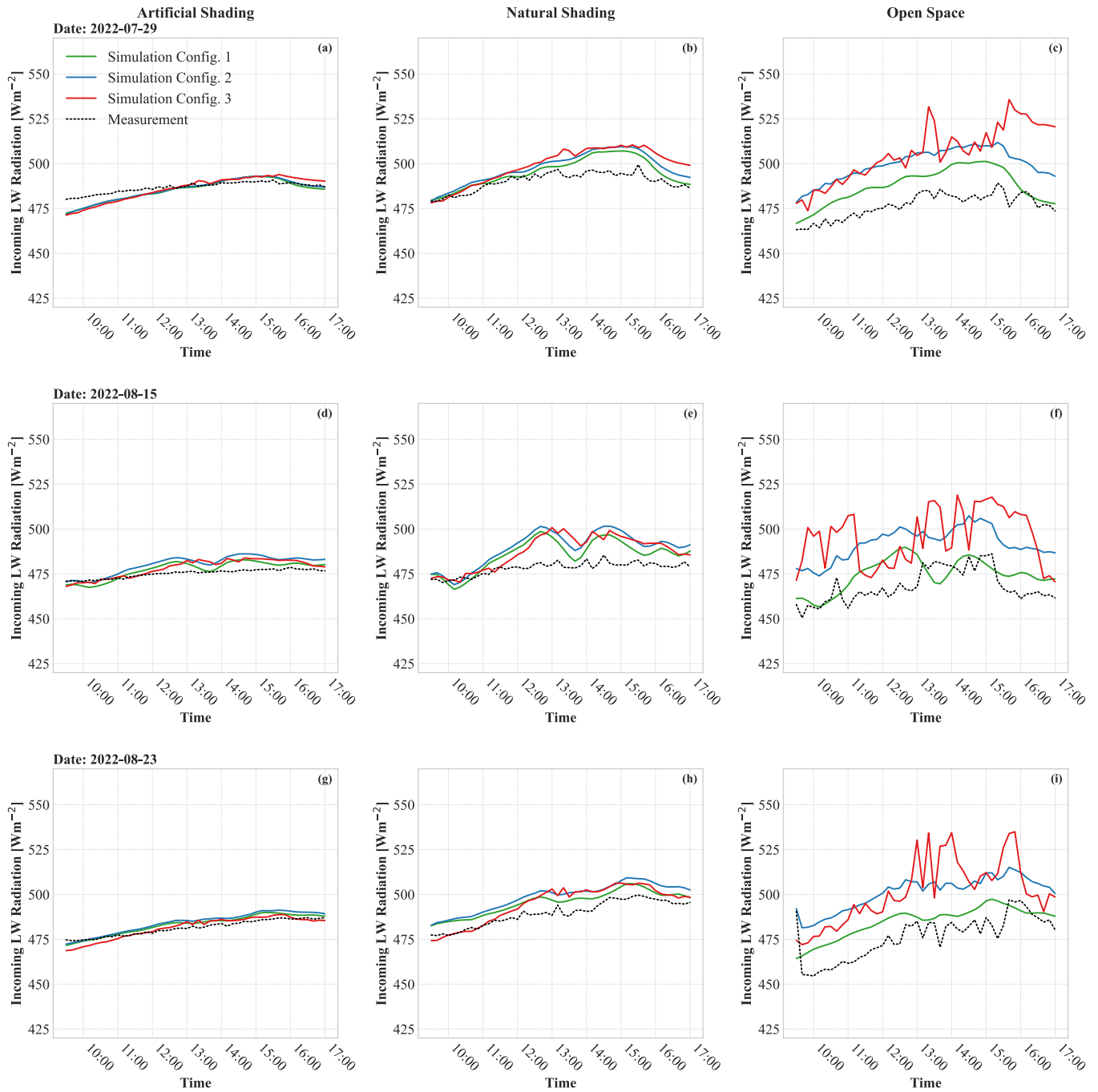


Fig A6. Comparison of Incoming Longwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

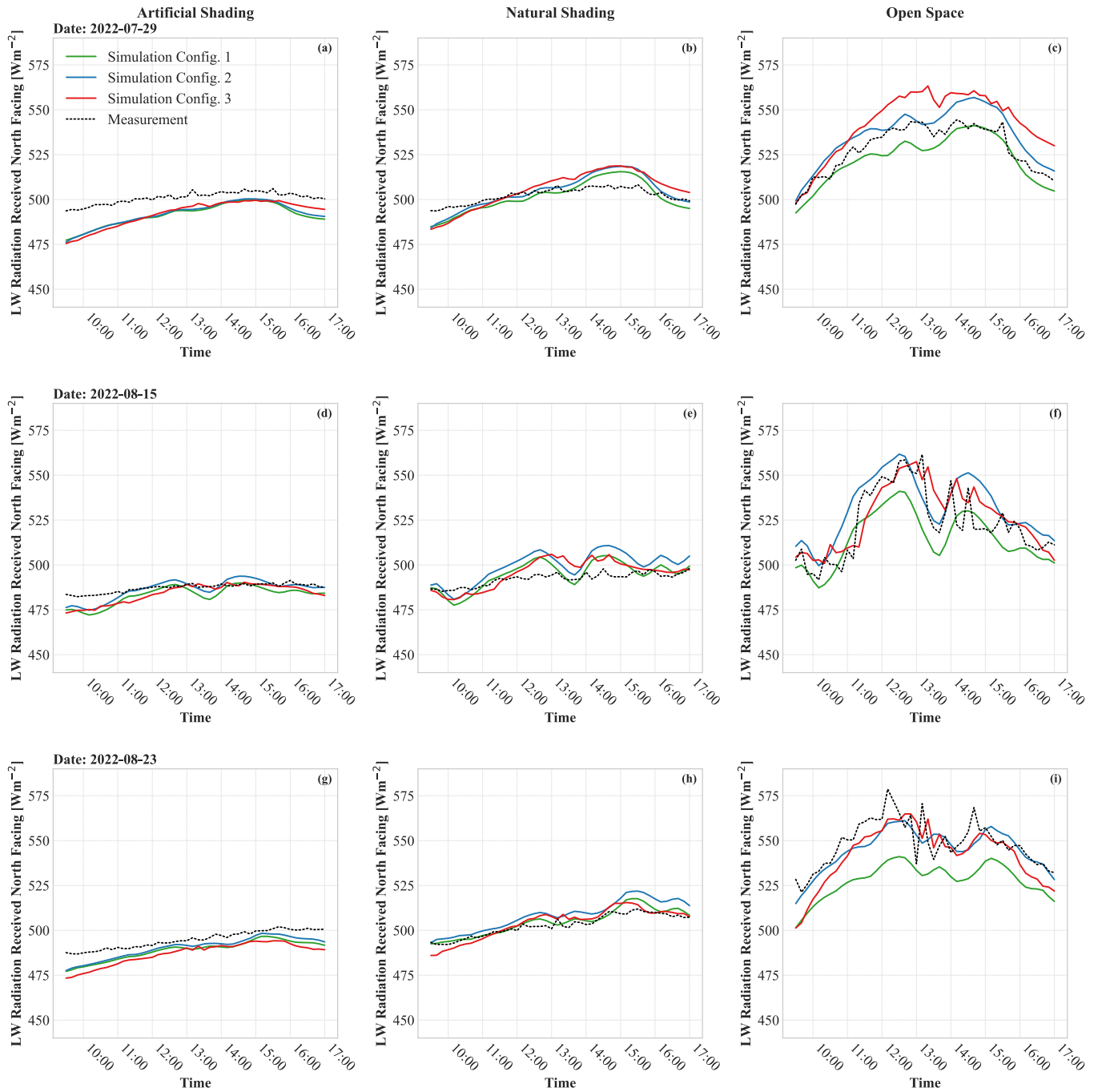


Fig A7. Comparison of Northward Longwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

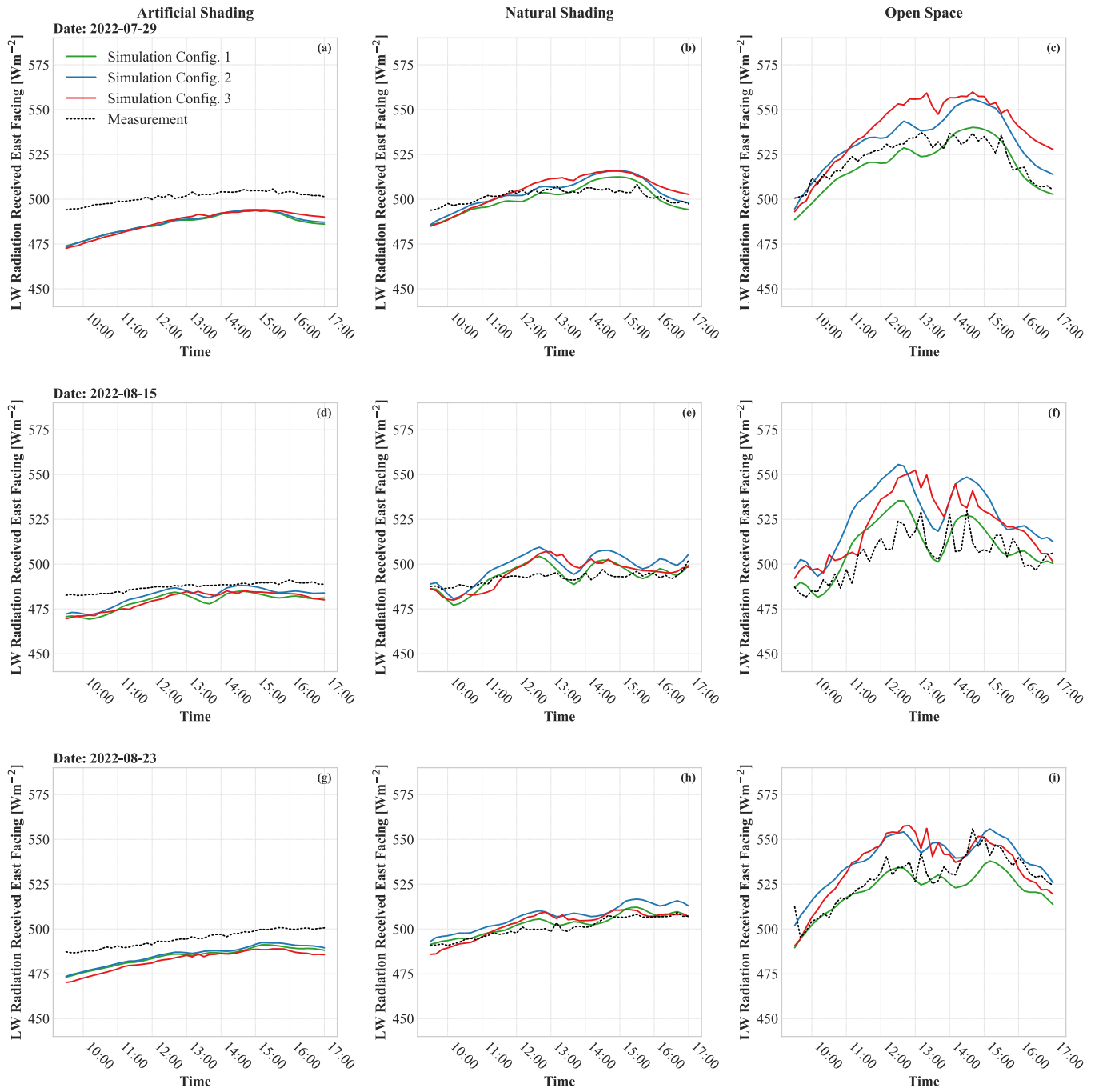


Fig A8. Comparison of Eastward Longwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

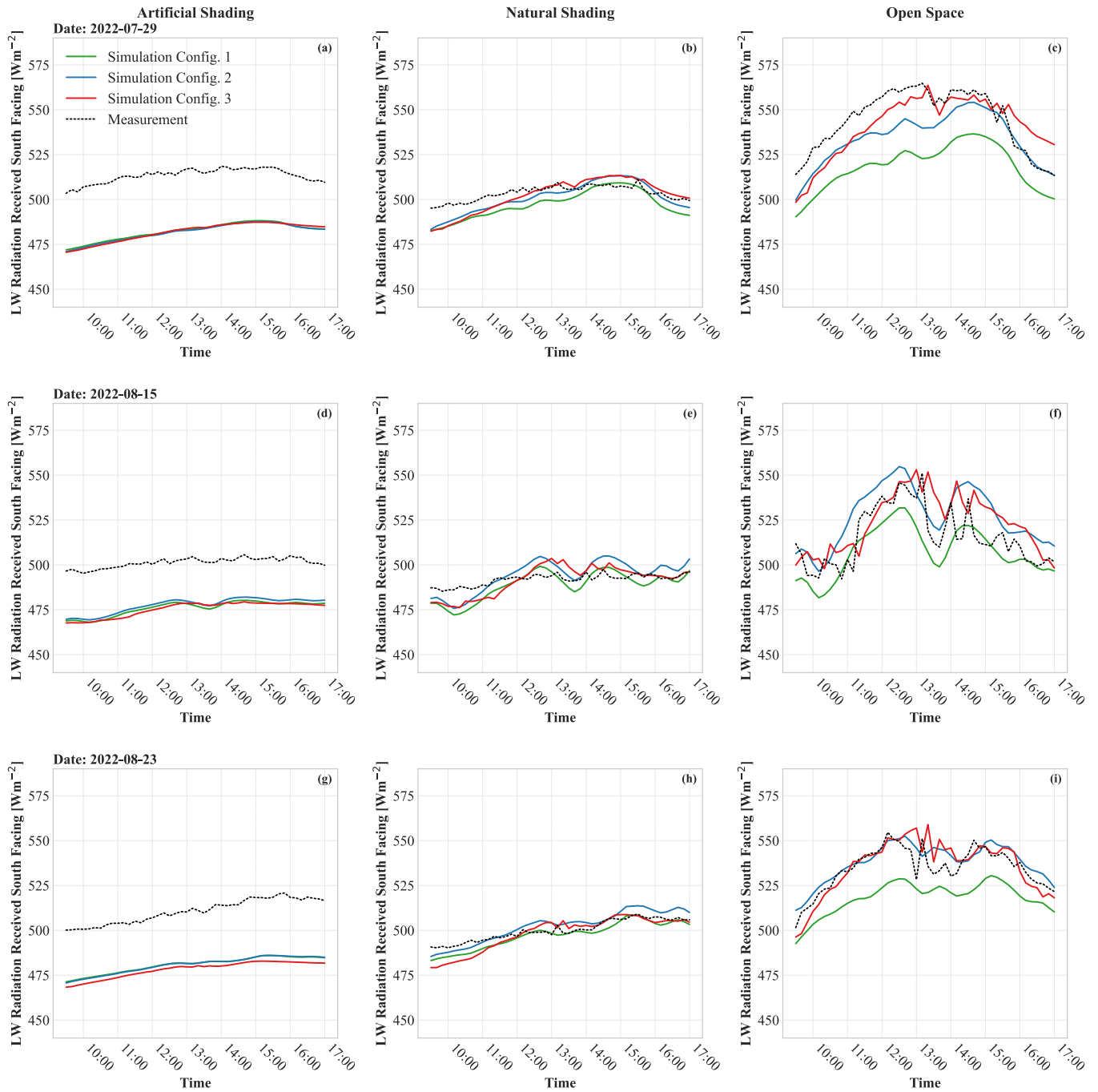


Fig A9. Comparison of Southward Longwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

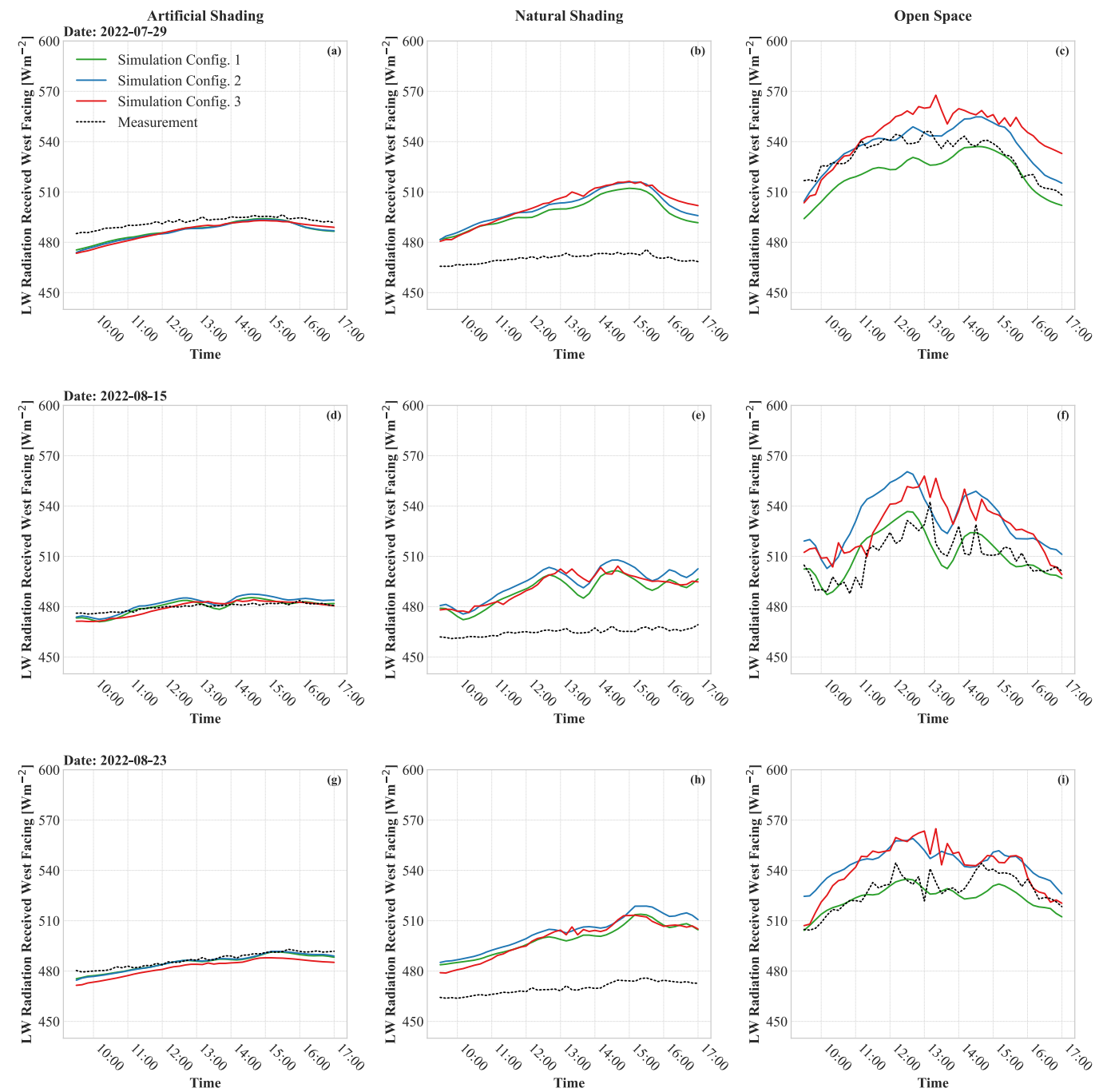


Fig A10. Comparison of Westward Longwave Radiation Fluxes Across Different Simulation Configurations and Measurement Data.

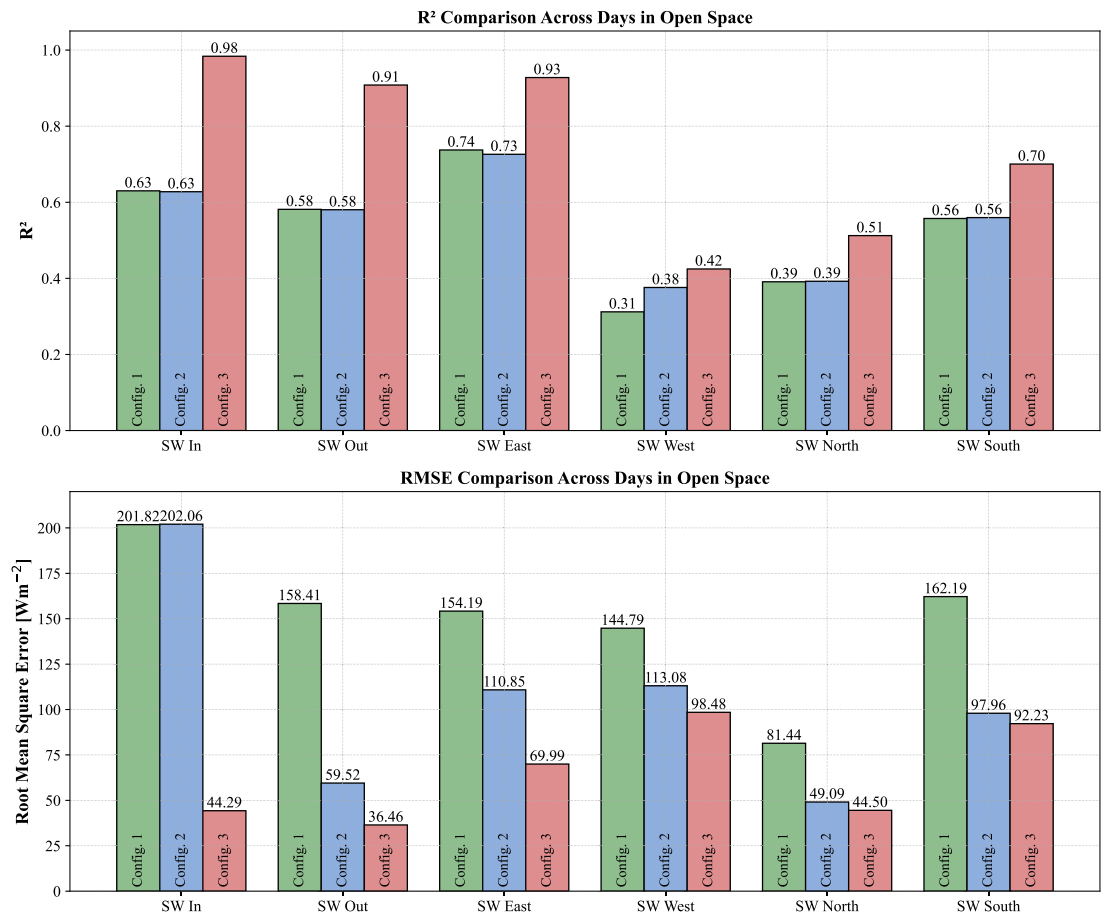


Fig A11. Presentation of R² and RMSE for Shortwave Radiation Fluxes Across Six Directions, Averaged Over All Days in Open Space.

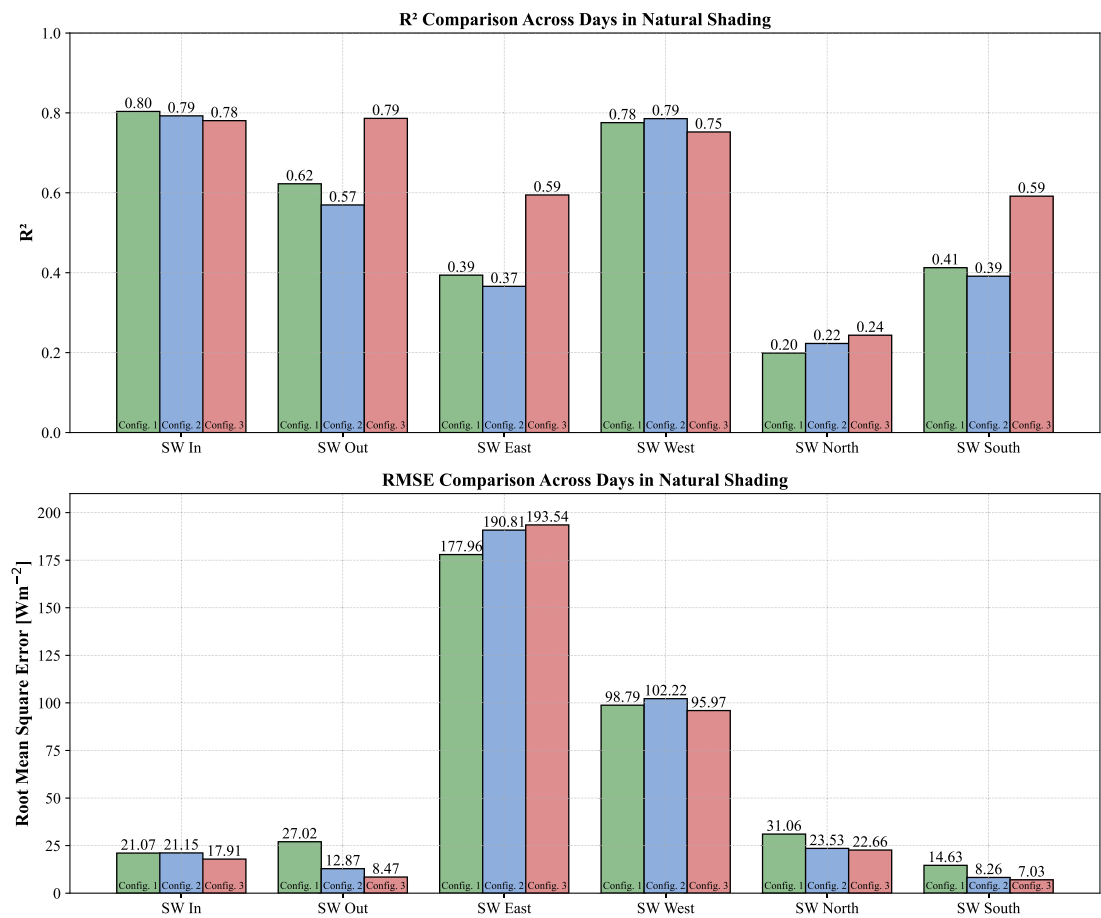


Fig A12. Presentation of R² and RMSE for Shortwave Radiation Fluxes Across Six Directions, Averaged Over All Days in Natural Shading.

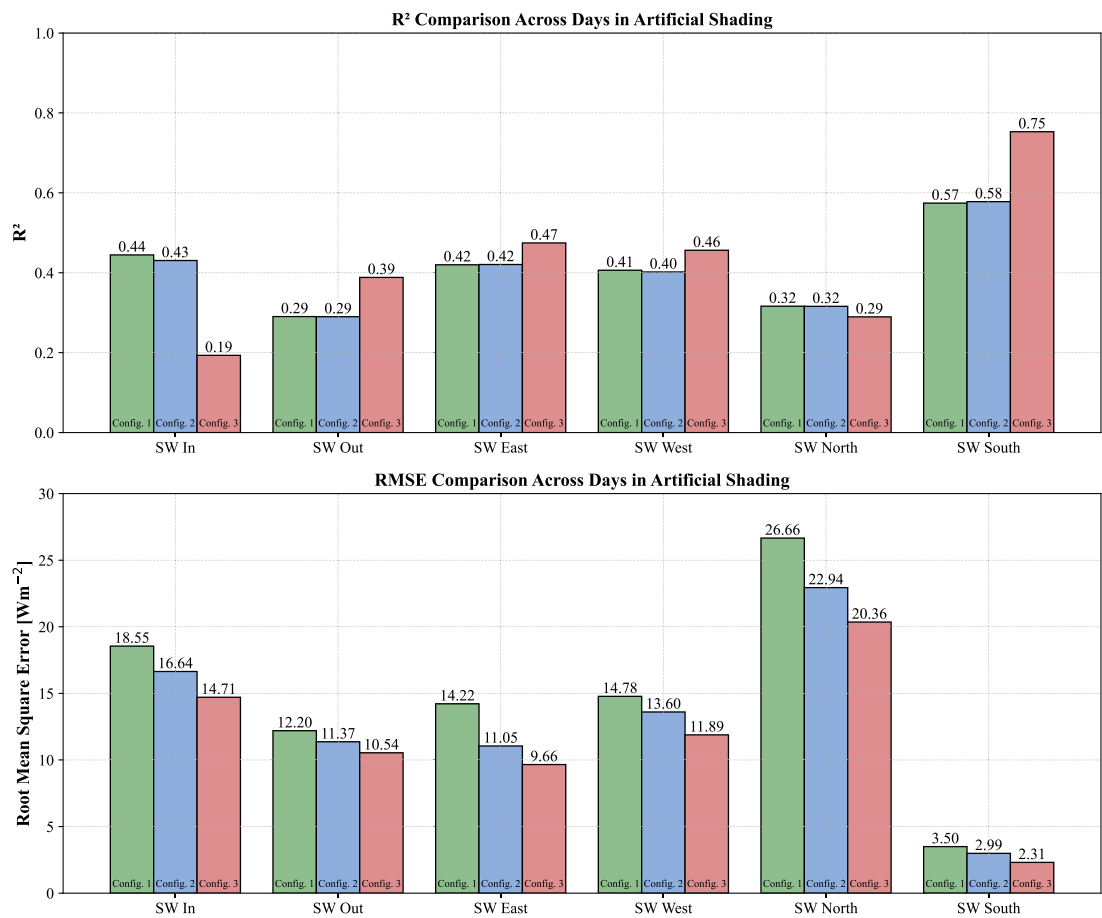


Fig A13. Presentation of R² and RMSE for Shortwave Radiation Fluxes Across Six Directions, Averaged Over All Days in Artificial Shading.

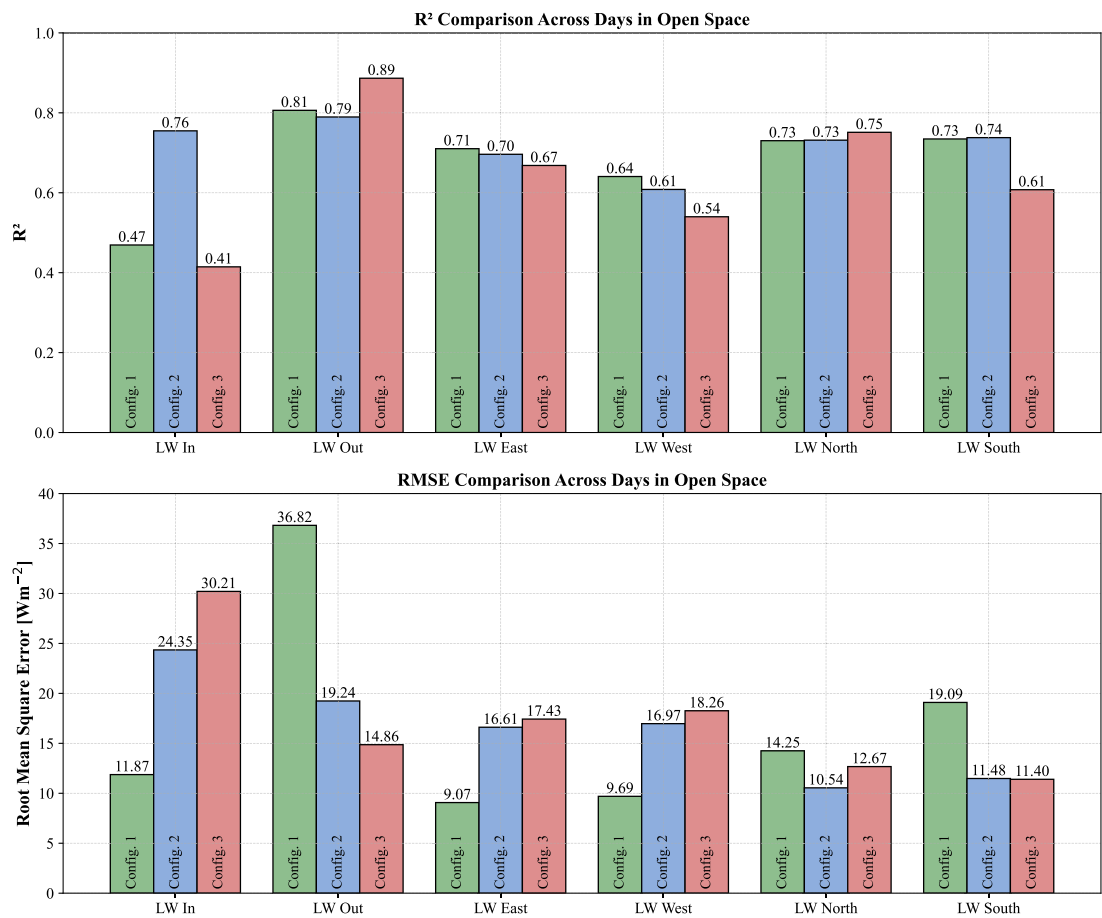


Fig A14. Presentation of R² and RMSE for Longwave Radiation Fluxes Across Six Directions, Averaged Over All Days in Open Space.

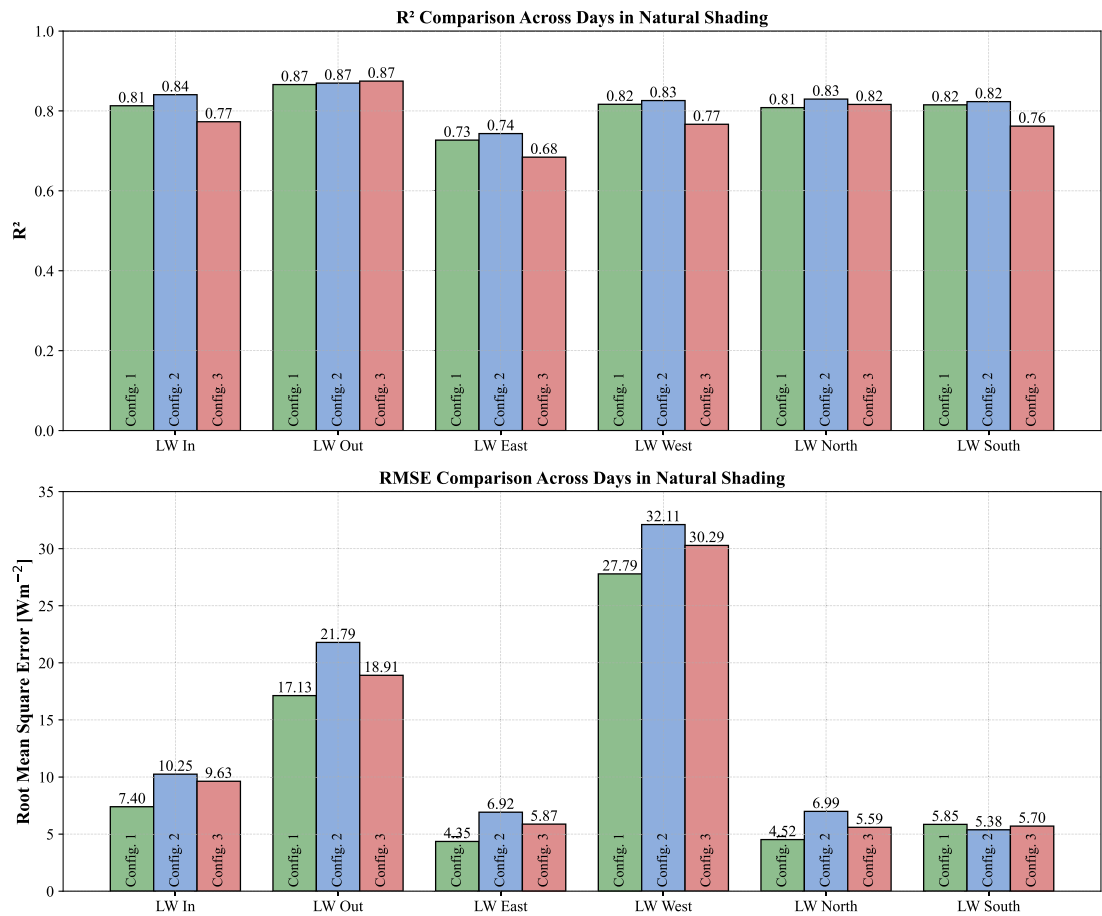


Fig A15. Presentation of R² and RMSE for Longwave Radiation Fluxes Across Six Directions, Averaged Over All Days in Natural Shading.

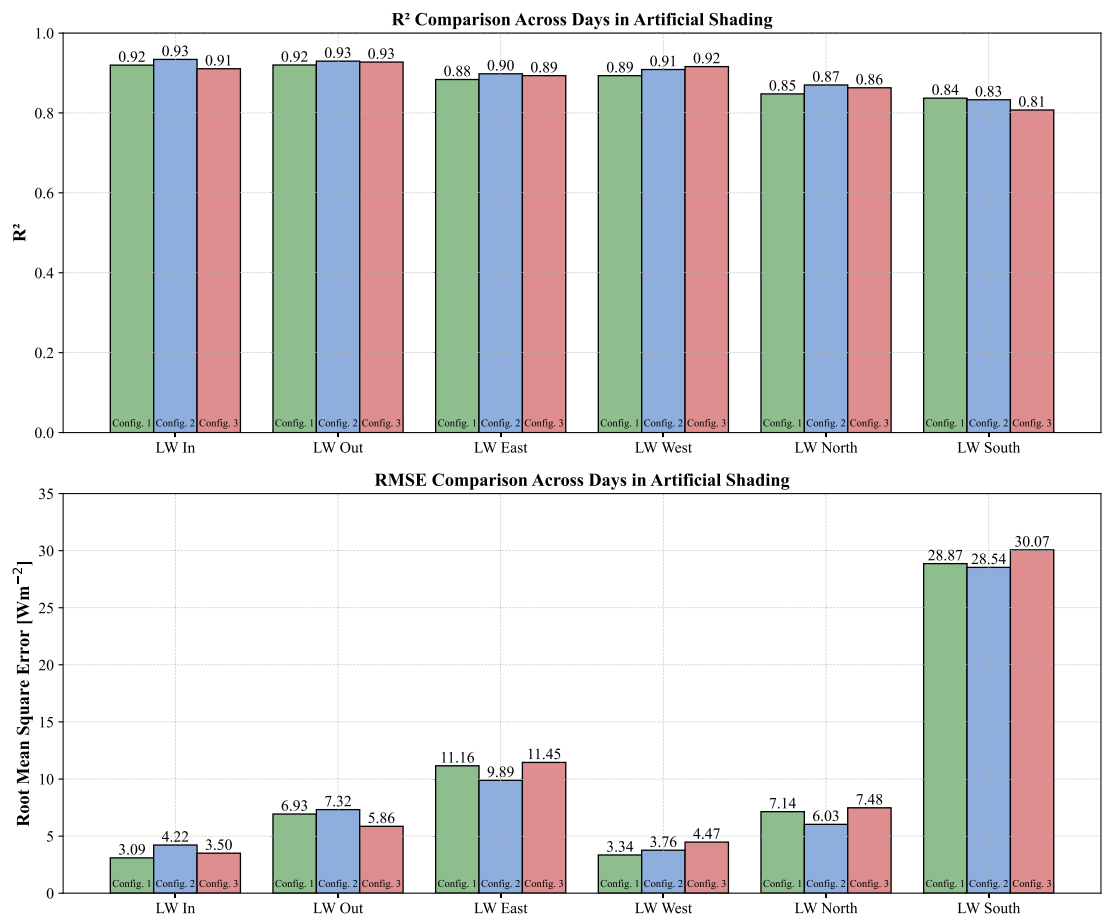


Fig A16. Presentation of R² and RMSE for Longwave Radiation Fluxes Across Six Directions, Averaged Over All Days in Artificial Shading.

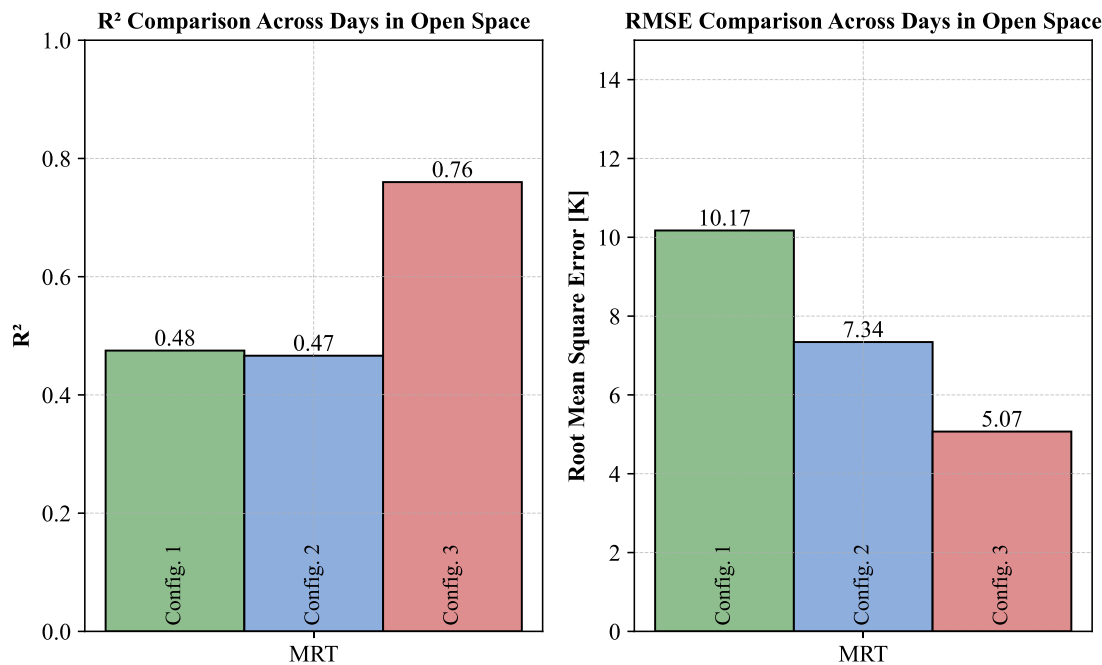


Fig A17. Presentation of R² and RMSE for MRT, Averaged Over All Days in Open Space.

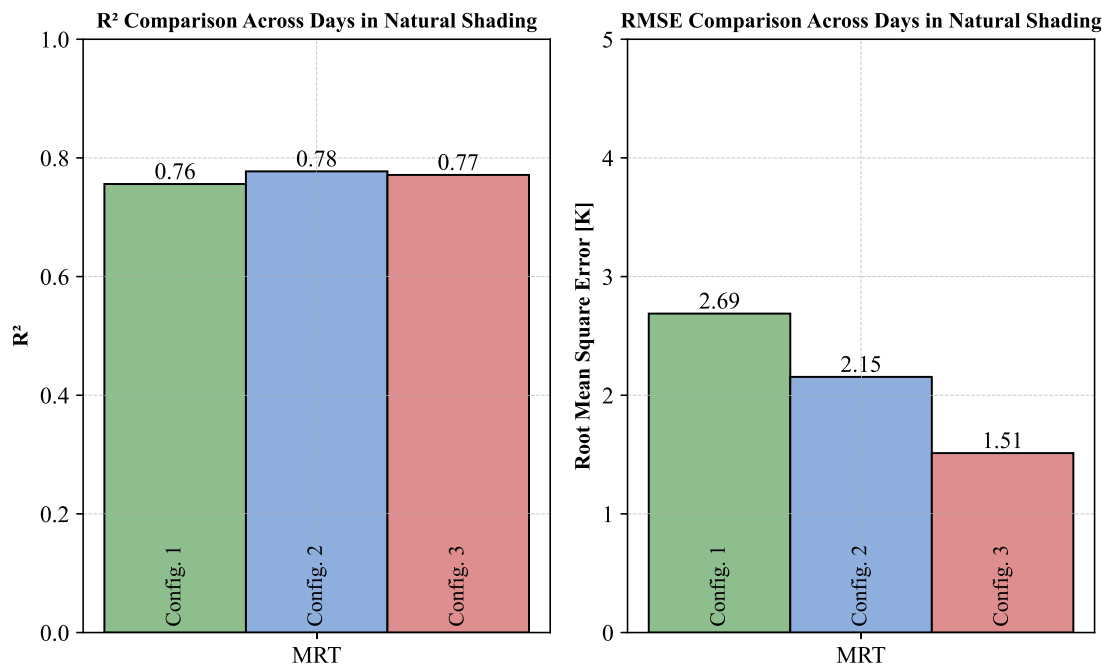


Fig A18. Presentation of R² and RMSE for MRT, Averaged Over All Days in Natural Shading.

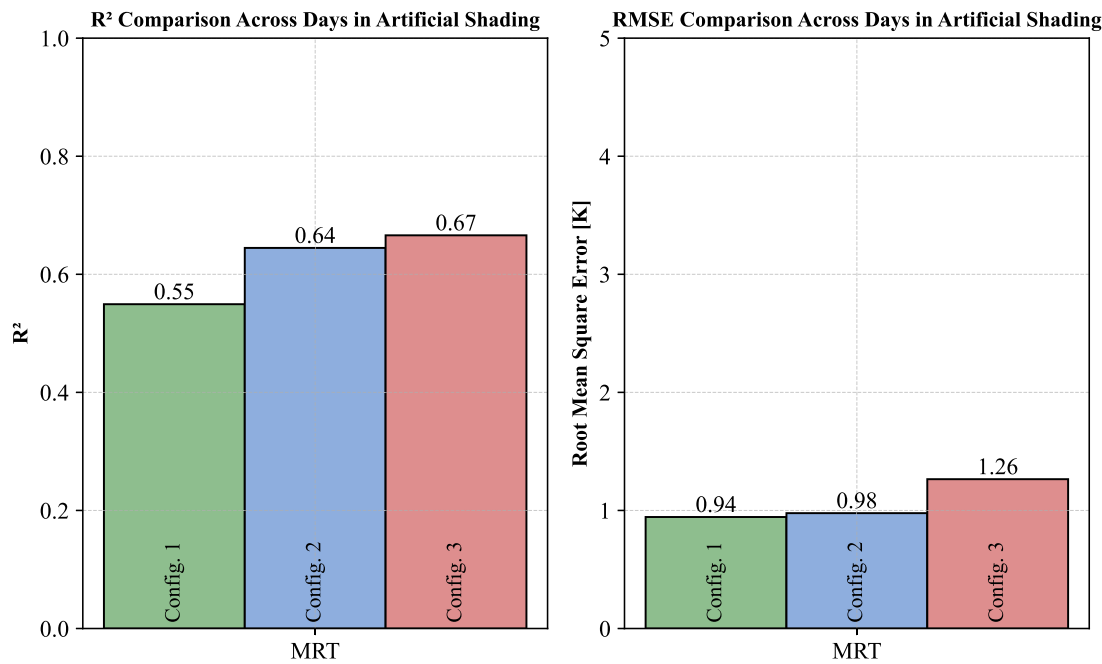


Fig A19. Presentation of R² and RMSE for MRT, Averaged Over All Days in Artificial Shading.

Appendix B. Simulation Data

[Fig B1](#), [Fig B2](#), [Fig B3](#), [Fig B4](#), [Fig B5](#), [Fig B6](#), [Fig B7](#), [Fig B8](#), [Fig B9](#), [Fig B10](#), [Fig B11](#), [Fig B12](#), [Fig B13](#), [Fig B14](#), [Fig B15](#), [Fig B16](#), [Fig B17](#), [Fig B18](#)

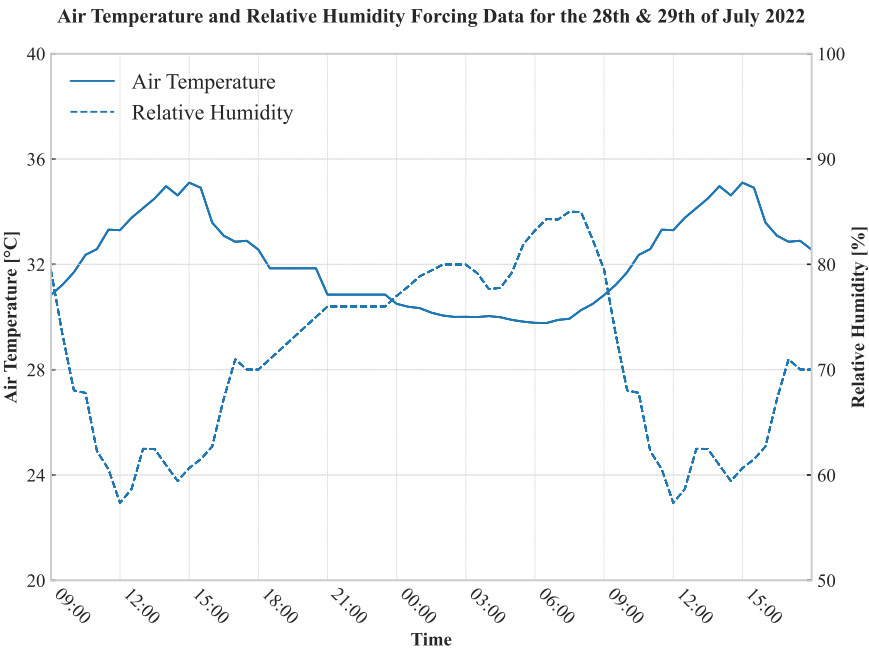


Fig B1. Boundary Values for Air Temperature and Relative Humidity for the ENVI-met Simulation of July 28 & 29, 2022.

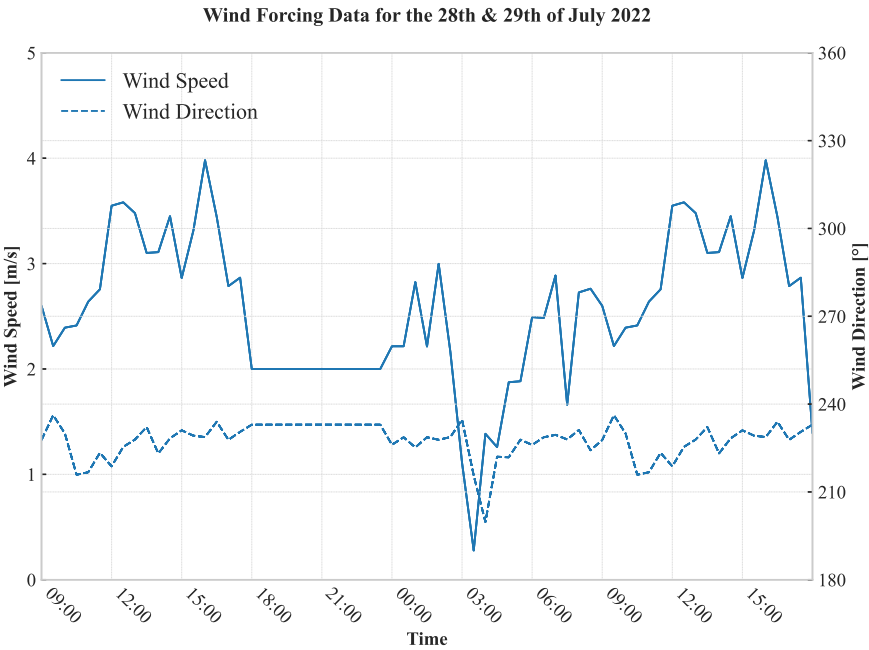


Fig B2. Boundary Values for Wind Speed and Wind Direction for the ENVI-met Simulation of July 28 & 29, 2022.

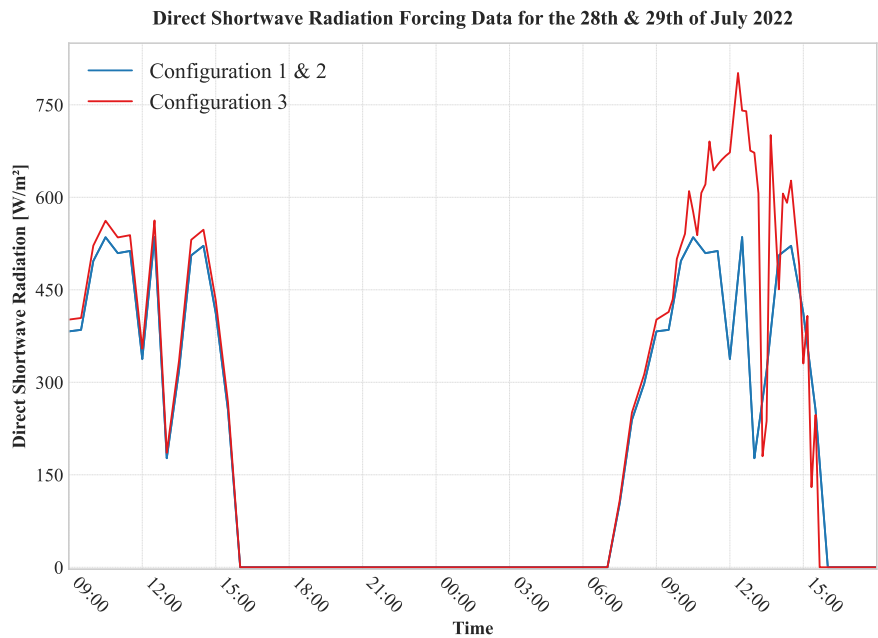


Fig B3. Boundary Values for Direct Shortwave Radiation for the ENVI-met Simulation of July 28 & 29, 2022.

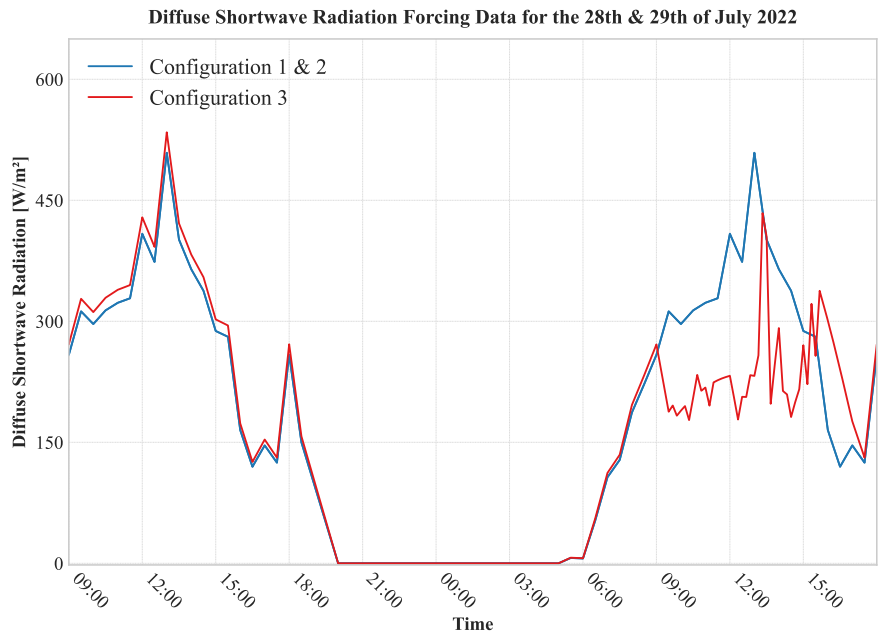


Fig B4. Boundary Values for Diffuse Shortwave Radiation for the ENVI-met Simulation of July 28 & 29, 2022.

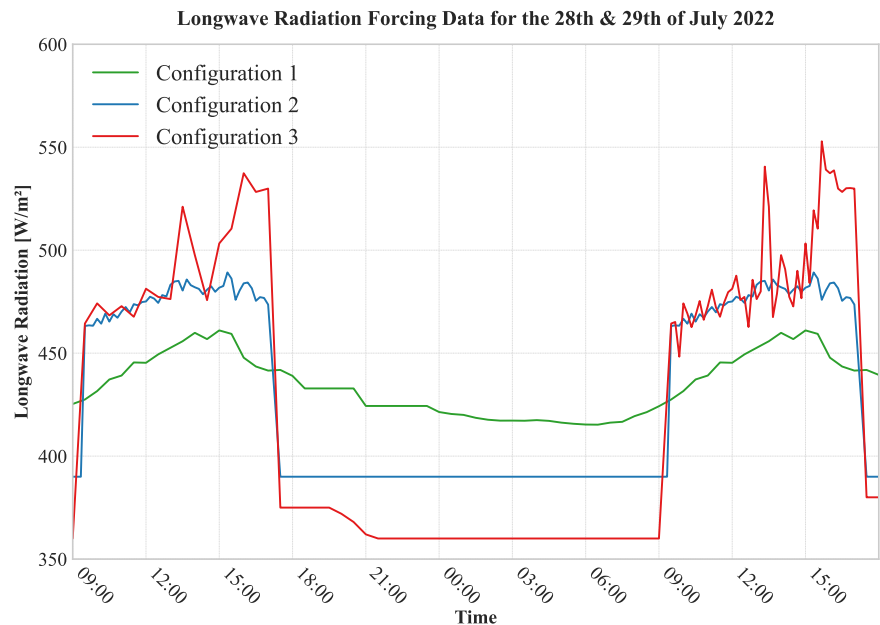


Fig B5. Boundary Values for Longwave Radiation for the ENVI-met Simulation of July 28 & 29, 2022.

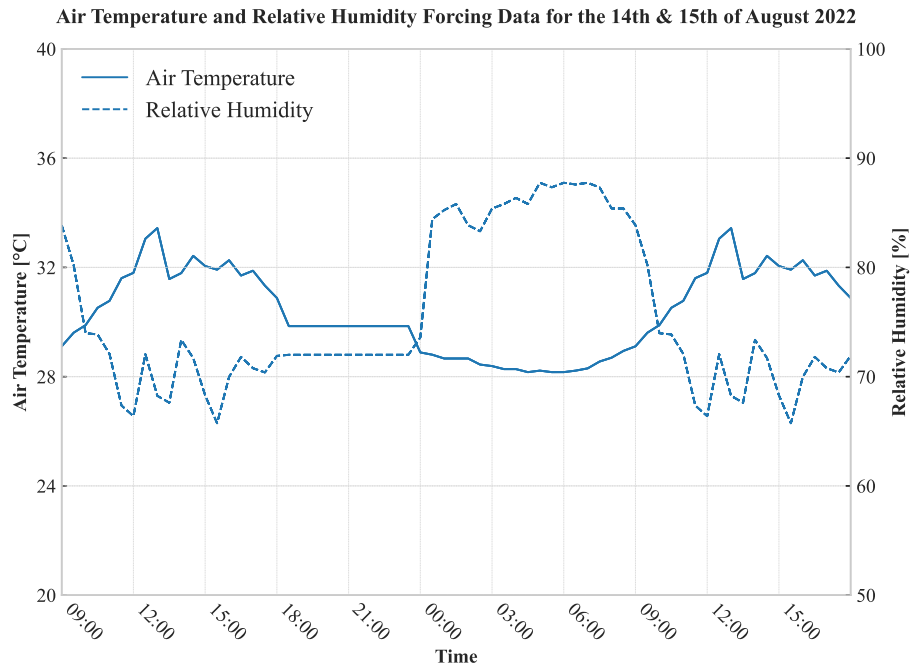


Fig B6. Boundary Values for Wind Speed and Wind Direction for the ENVI-met Simulation of August 14 & 15, 2022.

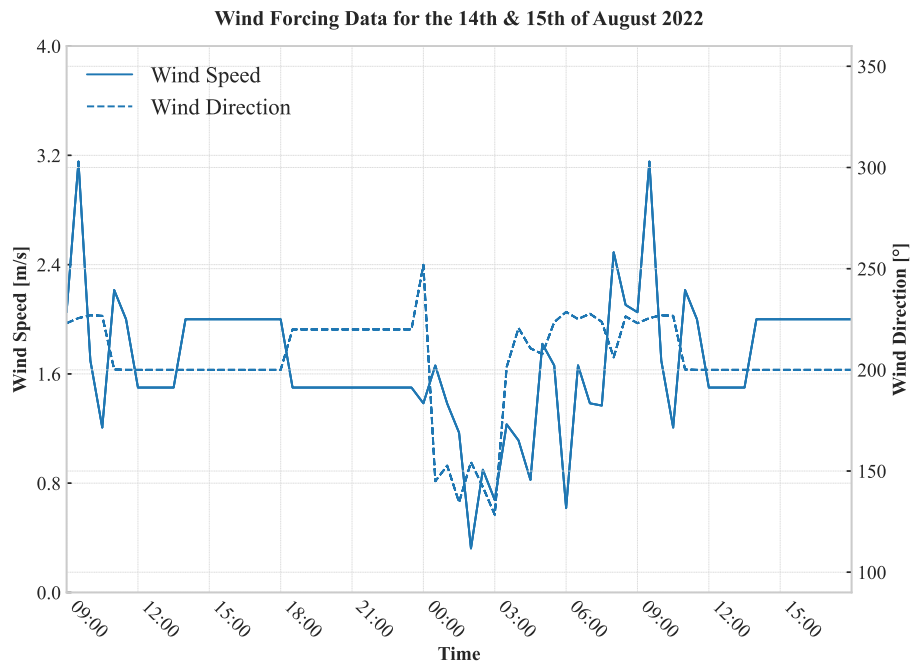


Fig B7. Boundary Values for Air Temperature and Relative Humidity for the ENVI-met Simulation of August 14 & 15, 2022.

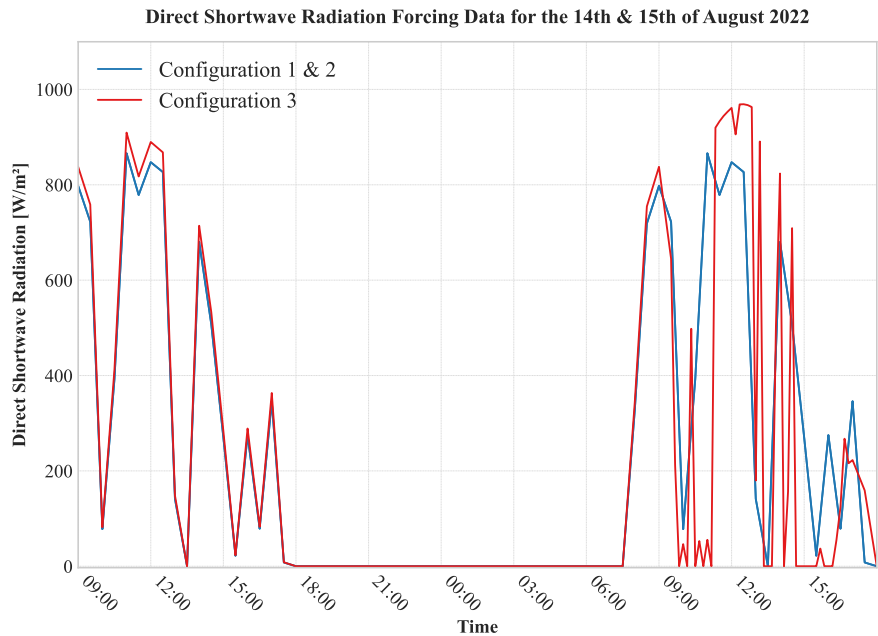


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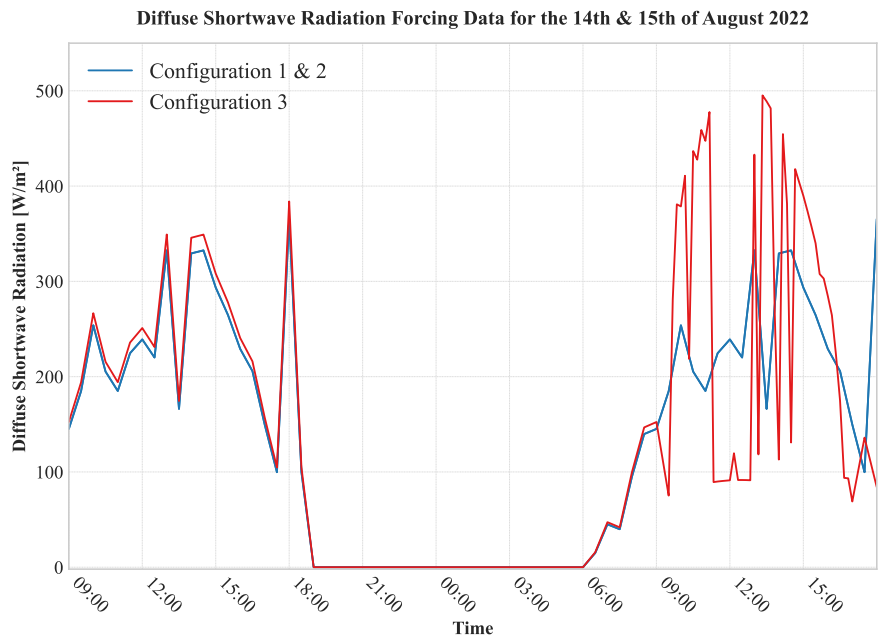


Fig B9. Boundary Values for Diffuse Shortwave Radiation for the ENVI-met Simulation of August 14 & 15, 2022.

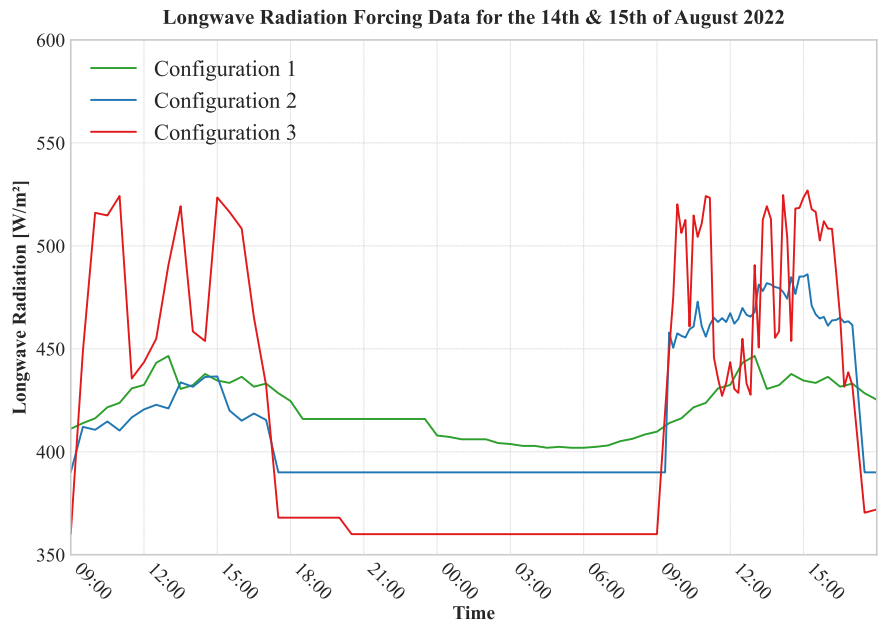


Fig B10. Boundary Values for Longwave Radiation for the ENVI-met Simulation of August 14 & 15, 2022.

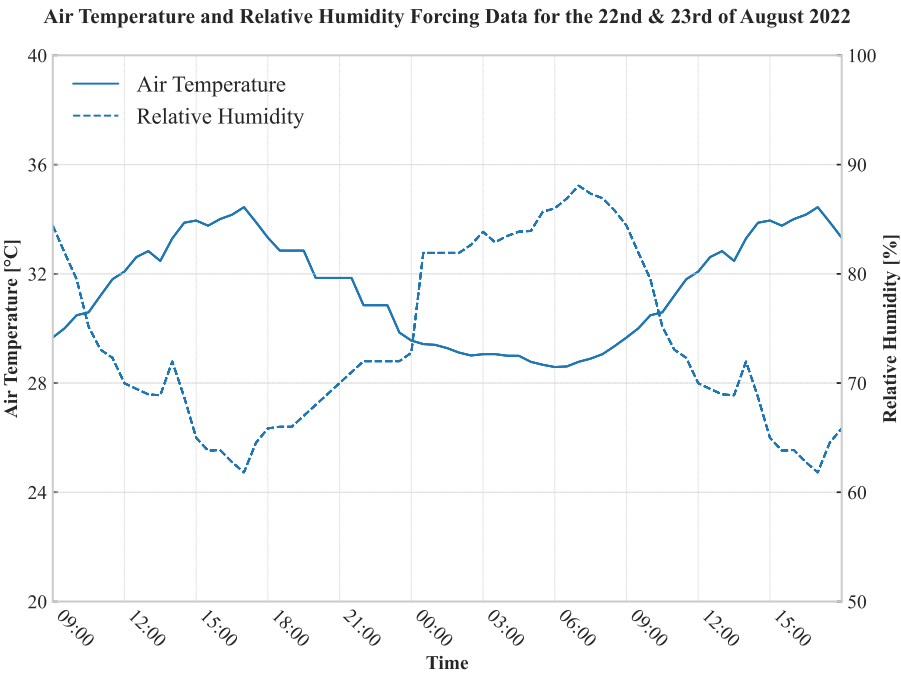


Fig B11. Boundary Values for Wind Speed and Wind Direction for the ENVI-met Simulation of August 22 & 23, 2022.

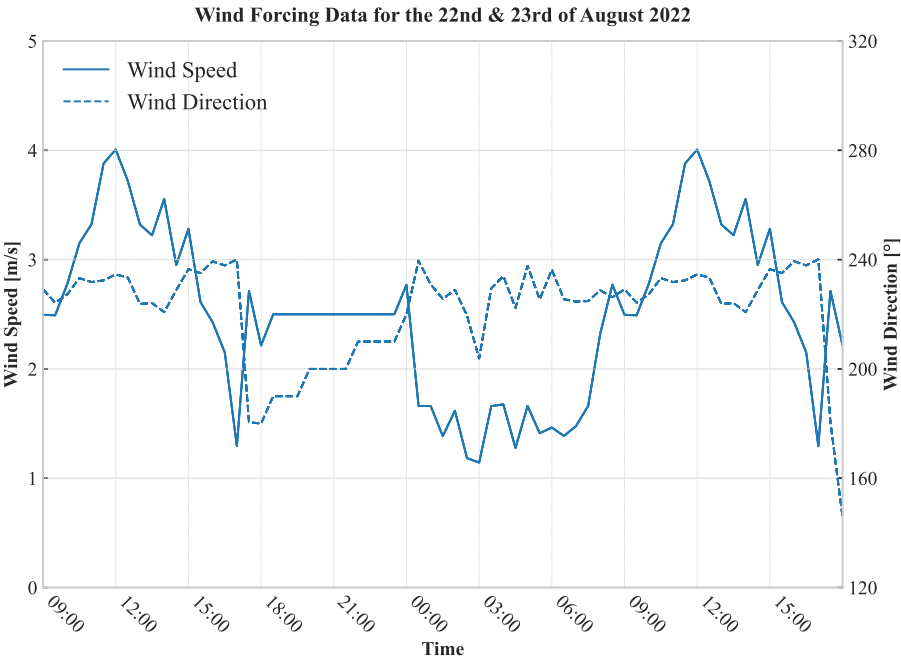


Fig B12. Boundary Values for Air Temperature and Relative Humidity for the ENVI-met Simulation of August 22 & 23, 2022.

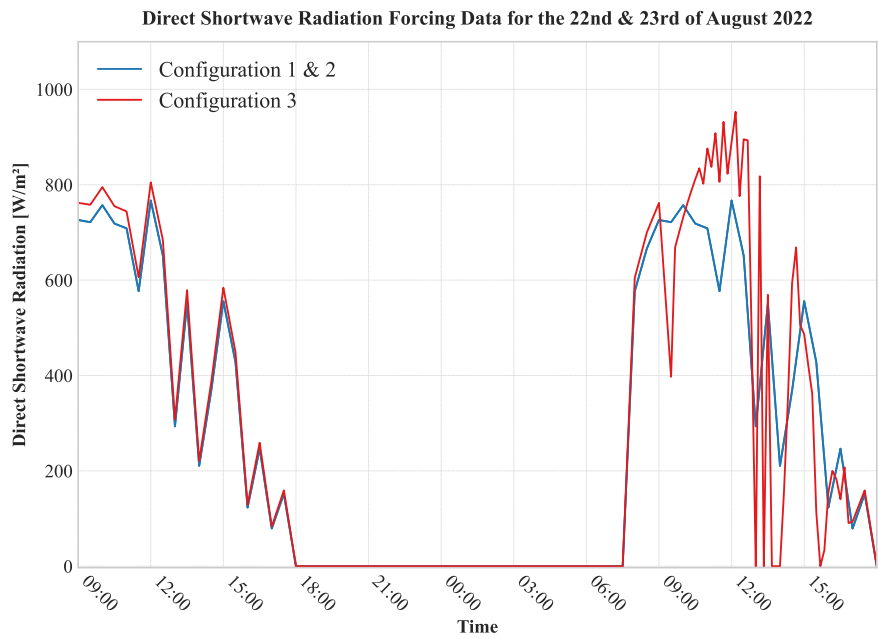


Fig B13. Boundary Values for Direct Shortwave Radiation for the ENVI-met Simulation of August 22 & 23, 2022.

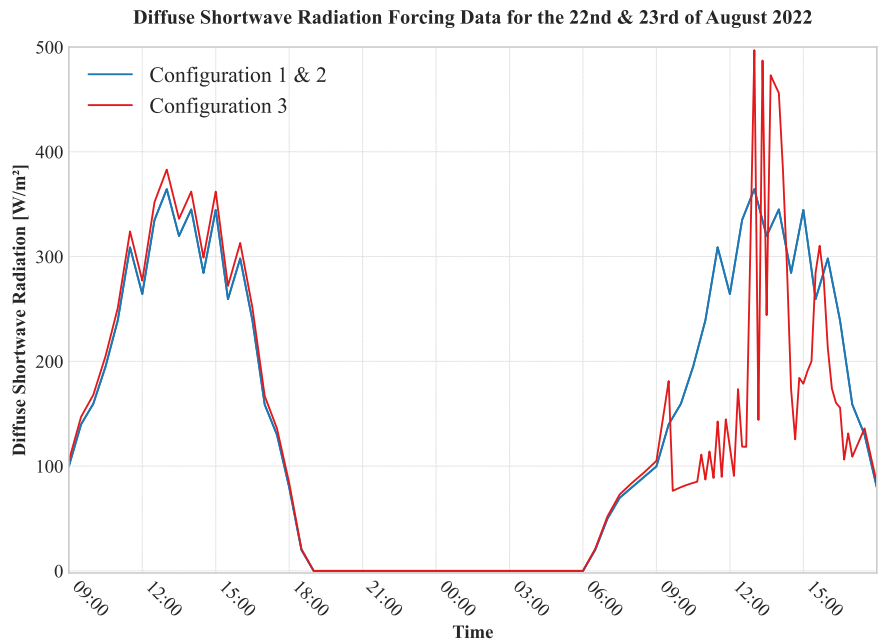


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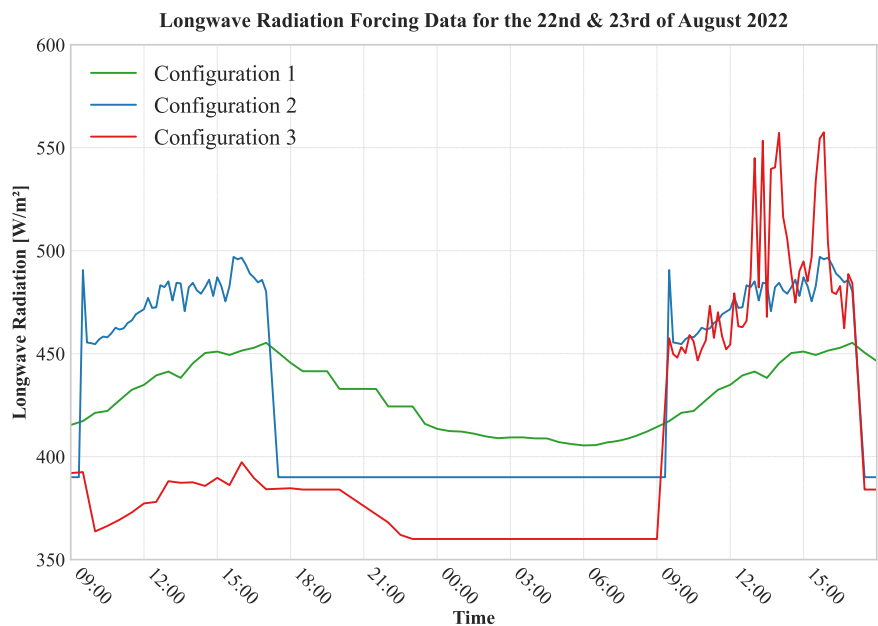


Fig B15. Boundary Values for Longwave Radiation for the ENVI-met Simulation of August 22 & 23, 2022.

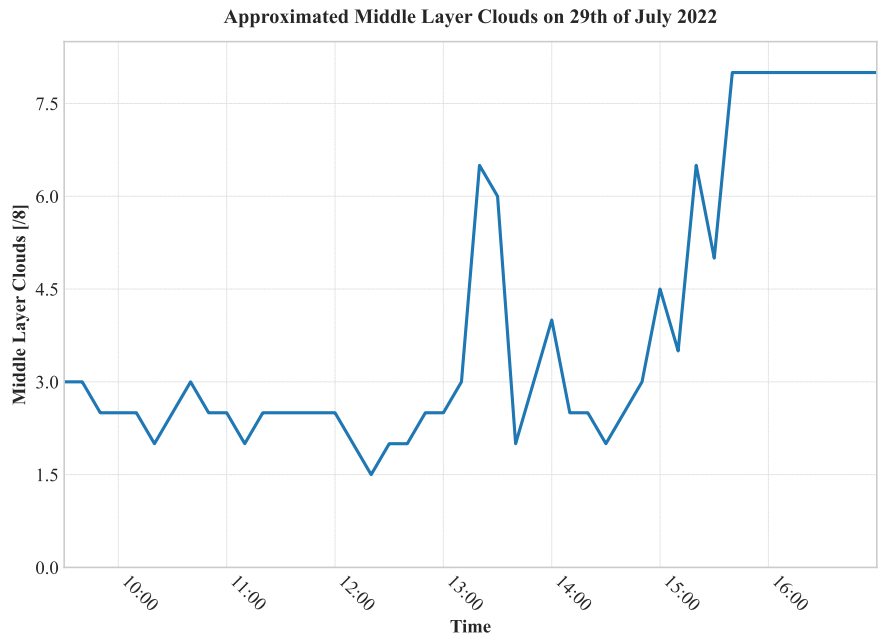


Fig B16. Approximated Middle Layer Clouds on 29th of July 2022.

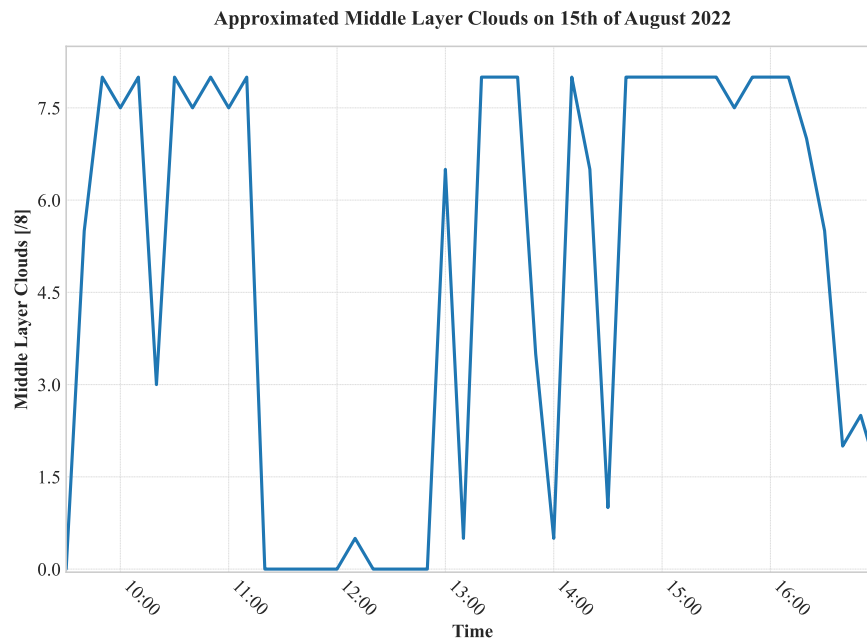


Fig B17. Approximated Middle Layer Clouds on 15th of August 2022.

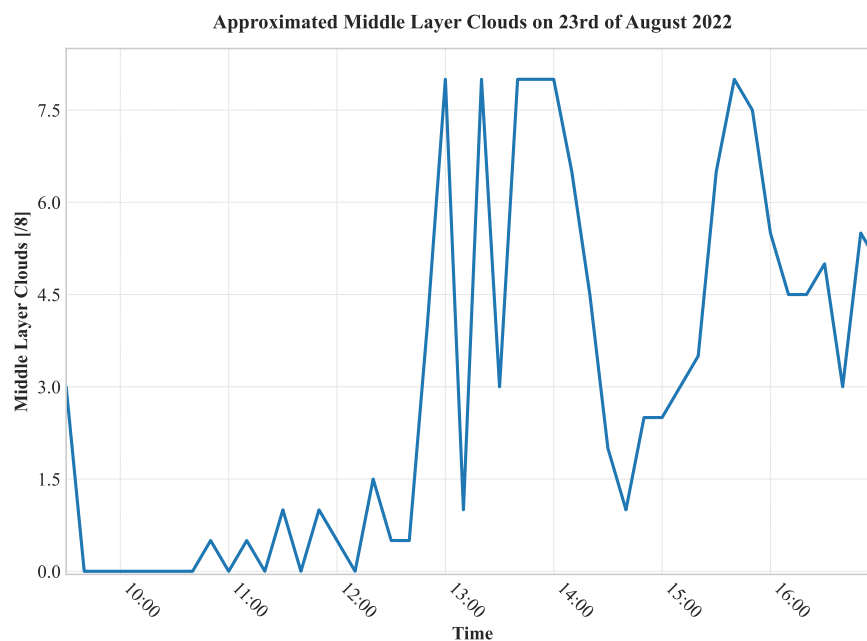


Fig B18. Approximated Middle Layer Clouds on 23rd of August 2022.

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