Maximizing the ENVI-met Capability of Modelling the Mean Radiant Temperature of a Tropical Archaeological Site

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Abstract. ENVI-met is one of the most widely-used outdoor microclimatic models. Since previous studies found that ENVI-met tends to overestimate the MRT, this study attempted to maximize the ENVI-met capability of modelling the MRT in order to obtain accurate simulation results. This study developed three variations of the 3D-model and employed some features to improve the large MRT discrepancy between the field measurement and simulation that resulted from the preliminary model. The field MRT measurements were conducted using a globe-thermometer method on two hot days, i.e., September 21 and October 17. After comparing the results of field measurements and simulations, this study came into a conclusion that the current free version software is capable of performing MRT predictions with a low discrepancy (5%) by using “Solar Adjustment Factor” and “Cloud Conditions” features (19.7% improvement), and maximizing the spatial resolution. The spatial resolution in z-axis decreases the discrepancy by 2.5%.

1. Introduction

Prambanan Temple Compounds is one of the UNESCO world heritages dedicated to the three great Hindu divinities (Trimurti) and visited almost two million visitors per year. However, most visitors suffered sweltering conditions due to the abundant solar radiation and radiative heat flux from the temple stones. Hence, it is essential to maintain a thermally comfortable tourist area for enhancing visitors’ well-being and increasing their arrivals.

Mean radiant temperature (MRT) is one of the essential meteorological parameters governing the human energy balance [1]. Most of the current outdoor thermal comfort indices take MRT into account [2]. Defining MRT value of an archaeological tourist area needs mobile/moving measurement. The globe-thermometer method provides accurate results of the mobile MRT measurement with a simple set-up [3]. Since MRT also considers a spatial metric and the influence of surface material [4,5], proper evaluation of an outdoor thermal environment should cover the entire study area. However, obtaining the MRT value of many points is expensive. At least many thermometers, anemometers, and globe thermometers equipped with data loggers, which represent the visitor circulation, are required to set-up [1,6]. Meanwhile, current computational simulations offer a more efficient and flexible method to estimate MRT value of many points in one area in (sub) hourly basis.

ENVI-met is a holistic microclimate software based on a 3D computational fluid dynamic model and an energy balance model that simulates the surface-plant-air interactions in an outdoor environment.
The capability in predicting bio-meteorological variables at a very high spatial resolution [7] and the availability of the free version with the acceptable accuracy make ENVI-met one of the most widely used outdoor microclimatic software [8-9]. ENVI-met calculates MRT using an equation, which is governed by some variables, i.e., the emission coefficient of the human body, the absorption coefficient of the human body for shortwave radiation, the incoming longwave radiation, and the incoming shortwave radiation [10]. Since the scattering of diffuse radiation towards upward and downward directions is considered isotropic [10], the predictions of MRT tend to estimate highly [3,11], although the modelling can predict the relative variations in MRT conditions between sites [11]. Because of the errors in estimating direct shortwave and diffused/reflected shortwave and longwave radiation, the MRT calculation might produce significant discrepancies from on-site measurements in Dhaka, Bangladesh [11]. Because ENVI-met only considers buildings' temperatures in a simplified way, it is only partially applicable to the fields with geometrically complex buildings and free-standing objects [5]. According to Sharmin et al. [11], ENVI-met is unable to distinguish between the precise details in urban geometry features. These limitations bring a challenge in the simulation study of the Prambanan Temple Compounds whose geometry is complicated. Maximizing the current free version ENVI-met capability of predicting the MRT, hence, is essential for further MRT simulations of areas with high solar radiation and complex geometry.

2. Methods

2.1. The object of the study

The Prambanan Temple comprises 240 temples built from andesite on a terraced yard. The Trimurti temples, i.e., Brahma (33 m high), Shiva (47 m high), and Vishnu (33 m high) temples, accompanied with their ‘vehicle’ temples lie on a 110x110 m² inner zone yard. Two hundred and twenty-four small shrines surround the inner zone, and most of them are currently still in ruins. The inner zone and Pervara temple zone cover a 222x222 m² area (Figure 1a). The inner zone is the visitor area of Prambanan Temple Compounds where the tourists can stroll, stand to observe the temples, or sit down on the lower part of the temple or under the trees. This area is located at the latitude of 7°45'S and the longitude of 110°30'E and 154 m above sea level and belongs to tropical rain forest (Koppen Af).

2.2. Globe thermometer method for field MRT measurements

ASHRAE [12] defines MRT as a uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure. There are several methods to measure and model MRT. Despite the less accurate method compared to the six-direction-radiation method, the globe-thermometer method is suitable for a mobile MRT measurement [3]. The globe-thermometer method calculates a MRT value using Equation (1).

\[ MRT = \left( (T_g + 273.15)^4 + (1.335 \times 10^8 V_a^{0.71}) / (\varepsilon D^{0.4}) \times (T_g - T_a) \right)^{0.25} - 273.15 \]  

(1)

The \( T_g \) and \( T_a \) represent the weighted average of the globe and ambient temperatures. \( V_a \) is wind velocity (m/s), \( D \) is the globe diameter (mm), and \( \varepsilon \) is globe emissivity. A 38 mm globe thermometer measures the \( T_g \). This study obtained the \( T_g \), \( T_a \), and \( V_a \) from measurements conducted by a moving surveyor. Equipped with a Testo 905i globe thermometer for measuring the \( T_g \), HOBO U12-012 for the \( T_a \), and Benetec anemometer GM-8902 for \( V_a \), the surveyor moved following the visitor position/circulation. The instruments’ accuracy complies with ISO 7726 [13]. Testo 905i was inserted into a hollow 38 mm ping pong ball painted in black matte (Nippon Pyloxx black matte). Testo 905i and HOBO U12-012 were mounted at 1.7-1.8 m above the ground on a wooden stick inserted into the surveyor’s backpack to prevent shadowing effect and heat transfer from the surveyor body to the instruments. The surveyor handed Benetec GM-8902 at the average height of 1.5 m. This study obtained incident solar radiation data at 1.5 m height above the ground (canopy layer) from the factory calibrated Solar Power Meter SP2065 and at the urban boundary layer (at 10 m height) were acquired from Ambient Weather 2902A. All data loggers were set up in 1 min interval and
averaged over 10 min. We conducted measurements on September 21, 2018 and October 17, 2018, where the sun was located respectively above the equator line and at the zenith.

2.3. ENVI-met: model setup, initialization, and simulation
Defining grid resolution is very important for MRT simulation [3]. The current free version (ENVI-met V4 Winter 1819) allows maximum grids up to 100 x 100 x 45 cells for x, y, and z-axis. This study used the 2 m resolution for the x and y-axis (respectively dx and dy) to maximize the grid resolution for the 222 x 222 m² area. The 100 x 100 grid-cell input area with 2 m resolution can cover the inner zone and the pervara-temple area. The determination of receptors’ location refers to surveyor positions (Figure 1b).

This study applied the Digital Elevation Model (DEM) for modelling the varying height of the terrain (Figure 1c). ENVI-met allows a maximum of 30 cells for z-axis regarding the turbulence reason. For best results, the vertical spacing should equal to the height of the highest element in the structure model. For this case, 4 m resolution for z-axis (dz) is the smallest dz for 30 cells that created a sufficient distance (61 m) from the highest element (57 m) to the model top (118 m).

ENVI-met provides a telescoping feature to refine the grid resolution near the ground by increasing the dz upward according to the telescoping factor. This study adopted two variations of the telescoping grid. ENVI-met generated Grid (1) using 0.35 m dz and 20% telescoping factor starting after the height of 2 m. This grid created 127.88 m for the height of the model top and 70.88 m for the distance from the highest point element to the model top, and 0.87-1.05 m for the dz at the visitor’s height (around 6.5 m from ±0.00 m levels). Grid (2) was generated by larger dz (0.55 m) that increased 20% starting at 5 m height. This grid created 118.17 m for the height of the model top and 61.17 m for the distance from the highest point element to the model top, and 0.55-0.95 m for the dz at the visitor’s height.

In order to maximize the ENVI-met capability of modelling the MRT, this study selected the advanced level. At this level, the user may set the soil temperature and humidity, cloud cover, solar adjustment factor (SAF), and new turbulence models. Since Indexed View Sphere (IVS) for accurate calculations of the solar radiation flux and Sky View Factor (SVF) [5] is not available in the free version, SAF was used to improve the accuracy of MRT calculation by putting a factor that describes the discrepancy between simulation and field measurement results. In the first simulation, all possible features were applied, except the SAF.
We measured the soil temperature and humidity (T\textsubscript{soil} and RH\textsubscript{soil}) using Espec RS-13 located in the area exposed to direct solar radiation. The initial wind (speed and direction) data and solar radiation data were acquired from the field measurement using Ambient Weather 2902A installed at 10 m high in an open area at Prambanan Temple Compound. As the simple forcing was selected, hourly Ta and RH data on September 21, 2018 and October 17, 2018 obtained from field measurements in the inner zone using PCE FWS-20 micro weather station were input.

This study analyzed the results by obtaining the discrepancies (d) between field measurement and simulation results, the Root Mean Square Error (RMSE) and the coefficient of determination (R\textsuperscript{2}). In this study, the discrepancy is useful to define the SAF. Generally, RMSE is used as a standard statistical parameter to measure model performance. Whereas, R\textsuperscript{2} was calculated to know how close the simulation results fit the measurement results.

3. Results

3.1. Field measured MRT
Field measurements on September 21 and October 17, 2018 resulted in 1-min resolution T\textsubscript{g}, T\textsubscript{s}, and V\textsubscript{a} data. Table 1 presents the hourly MRT that was calculated using Equation (1), and 10 min averaged data of T\textsubscript{g}, T\textsubscript{s}, and V\textsubscript{a}. The Sky View Factor (SVF)s were calculated using the SVF calculator based on the fish-eye photos of the open spaces [15]. Where, the cloud cover was obtained from visual observation synchronized to the online local meteorological report [16].

| Time   | September 21 |   | October 17 |   |
|--------|--------------|---|------------|---|
|        | SVF | T\textsubscript{s} (°C) | T\textsubscript{g} (°C) | V\textsubscript{a} (m/s) | MRT (°C) | Cloud (°) | SVF | T\textsubscript{s} (°C) | T\textsubscript{g} (°C) | V\textsubscript{a} (m/s) | MRT (°C) | Cloud (°) |
| 09:00  | 0.90 | 30.2 | 37.03 | 0.85 | 38.4 | 4 | 0.68 | 33.8 | 39.57 | 1.90 | 40.8 | 3 |
| 10:00  | 0.74 | 31.7 | 39.44 | 1.09 | 41.1 | 1 | 0.82 | 35.2 | 40.48 | 2.80 | 42.4 | 3 |
| 11:00  | 0.95 | 32.8 | 46.01 | 1.70 | 48.5 | 1 | 0.92 | 38.2 | 43.28 | 1.62 | 47.0 | 2 |
| 12:00  | 0.87 | 34.7 | 42.58 | 1.18 | 44.4 | 1 | 0.92 | 39.3 | 45.15 | 1.13 | 47.0 | 2 |
| 13:00  | 0.92 | 36.1 | 45.65 | 1.48 | 47.8 | 1 | 0.90 | 38.6 | 44.03 | 0.98 | 45.7 | 3 |
| 14:00  | 0.92 | 32.9 | 39.58 | 2.99 | 42.8 | 3 | 0.87 | 38.0 | 40.75 | 1.03 | 42.3 | 3 |
| 15:00  | 0.95 | 32.4 | 37.26 | 3.08 | 40.4 | 3 | 0.98 | 41.5 | 41.67 | 1.77 | 44.1 | 3 |
| 16:00  | 0.95 | 31.4 | 35.59 | 2.26 | 38.1 | 2 | 0.98 | 36.5 | 35.45 | 1.55 | 37.4 | 1 |

3.2. The first MRT simulation
The first MRT simulation was run using the Model 1 without advanced features, except the simple forcing. Table 2 presents the comparison between first simulation and field measurement results that resulted in large discrepancies and RMSEs, i.e., 20.2 (on September 21) and 16.3 (on October 17). Large discrepancies (> 25%) mainly occurred in the morning and afternoon. The small discrepancies (< 25%) that occurred at 11:00 to 12:00 on both dates agree with the results of the study conducted by Chen et al. [3]. Both studies confirm that ENVI-met predicts the MRT in midday more accurately than other times.

| Time   | September 21 | October 17 |
|--------|--------------|------------|
|        | MRT\textsubscript{m} (°C) | MRT\textsubscript{s} (°C) | Discrepancy (%) | MRT\textsubscript{m} (°C) | MRT\textsubscript{s} (°C) | Discrepancy (%) |
| 09:00  | 38.4 | 62.0 | 38.1 | 40.8 | 59.2 | 31.0 |
| 10:00  | 41.1 | 63.7 | 35.5 | 42.4 | 57.4 | 26.1 |
| 11:00  | 48.5 | 56.1 | 13.6 | 45.5 | 48.3 | 5.7 |
| 12:00  | 44.4 | 54.0 | 17.7 | 47.0 | 48.8 | 3.6 |
3.3. Solar adjustment factor
Since the first ENVI-met simulations tend to overestimate the MRT, the next step is determining the SAF by calculating the ratio between the field measured and ENVI-met simulated solar radiation. The average discrepancies are 32.4% for September 21 and 25.6% for October 17. The SAF of each simulation (date) was determined by the differences between 100% and the average discrepancies, i.e., 67.6% for September 21 and 74.4% for October 17.

3.4. Results of solar adjusted MRT simulations
Values of solar radiation in the next simulations were adjusted using the SAFs. Table 3 presents the results of solar adjusted MRT simulations and discrepancies between measured and simulated MRT. It also shows that the SAF and Cloud Condition features reduce the discrepancy by at least 19.7% and the RMSE of 13.8, whereas the telescoping grid improves the discrepancy up to 2.5% and the mean error up to 1.3.

| Date          | Average discrepancy (%) | RMSE   |
|---------------|-------------------------|--------|
| September 21  | Avg. discrepancy (%)    |        |
|               |                         | MRT_m1 | MRT_m2 | MRT_m3 |
|               |                         | 4.01   | 3.97   | 2.13   |
|               | RMSE                    | 2.24   | 2.42   | 1.31   |
| October 17    | Avg. discrepancy (%)    |        |
|               |                         | 11.41  | 9.92   | 8.37   |
|               | RMSE                    | 5.82   | 5.03   | 4.21   |
|               | Total discrepancy (%)   | 7.71   | 6.95   | 5.25   |
|               | Total RMSE              | 4.41   | 3.95   | 3.12   |
|               | $R^2$                   | 0.54   | 0.59   | 0.68   |

Telescoping grid applied in Model 3 resulted in better performance than the one applied in Model 2, i.e., 1.7 % in discrepancy and 0.83 in RMSE. The best performance of MRT simulations occurs on September 21 at 11:00 and on October 17 at 10:00 in three models. Most significant discrepancies appeared in the three models on October 17 at 13:00 – 15:00. In contrast to the consistent discrepancy patterns of the three models on October 17, on September 21 a distinct pattern revealed in the Model 3. The $R^2$ explains that only the MRT simulation results of the Model 3 fit well to the measurement results (the $R^2 > 0.6$).

4. Discussions
Although the IVS, is not available in the free version, SAF, Cloud Conditions and spatial resolution can be applied to improve the accuracy in calculating the MRT. Results presented in Table 3 indicate that the combination of the SAF and Cloud Conditions features is the most effective and straightforward method to reduce the MRT discrepancy. Since radiation in ENVI-met is considered isotropic [10], accurate simulation results can be achieved without using this feature if the simulation date is under a cloudless sky [8]. In this study, however, the simulation dates were mostly taken under cloudy skies (1-4 octas); hence, the cloud conditions should be input.

An interesting pattern appears when comparing solar radiation discrepancies and the cloud cover data. To obtain the correlation between two factors, we conducted bivariate analysis (statistical regression). The $R^2$ (0.685) and the statistical significance (0.0034) of the regression model with the $P = 0.95$.
explain that the cloud conditions and the discrepancies of solar radiation simulations have a similar
tendency, although the correlation is not very strong.
The spatial resolution can be maximized in x- and y-axis, as well as z-axis. The results presented in
Table 3 explain the significant role of the telescoping grid. Telescoping grid includes choosing the
lowest dz, starting point, and telescoping factor that should consider the top of the element/building,
dz at the height of the user/visitor and z₀. Discrepancies between measured and simulated MRT in
Table 3 show that dz at the measurement height (the user/visitor’s height) is the most crucial factor.
The smallest dz at the measurement height in the Model 3 (0.55-0.95 m) generates the most refined
grid that enables to perform the smallest discrepancy between measured and simulated MRT. Despite
the smaller lowest dz, the Model 2 has larger dz at the measurement height, i.e., 0.87-1.05 m.
Telescoping grid can save the simulation time. Using the same computer, a simulation of the Model 1
took 69h 48m 41s. Meanwhile, a simulation of Model 2 and Model 3 only spent 42h 15m 19s and 45h
59m 7s respectively.

5. Conclusion
Although the Indexed View Sphere is not available in the free version of ENVI-met program, this
program is still capable to accurately represent the MRT of the Prambanan Temple Compounds. A
highly accurate prediction of MRT (95%) has been achieved by using Solar Adjustment Factor (SAF)
and Cloud Conditions features and maximizing the spatial resolution. The combination of SAF and
Cloud Conditions can improve the accuracy in predicting the MRT. The Cloud Conditions feature is
useful if we take the simulation date under cloudy skies. Model 2 and Model 3 applied the
telescoping grid to refine the grid size in the z-axis. MRT simulation results of Model 3 achieved the
smallest discrepancy by increasing the z-axis resolution at the measurement (user/visitor's) height.

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**Acknowledgments**
Authors gratefully acknowledge the funding from USAID through SHERA program – Centre for Development of Sustainable Region (CDSR).