environmental sciences proceedings

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Proceeding Paper

A Study Regarding the Thermal Environment and Thermal Comfort during the 2021 National Intercollegiate Athletic Games and Related Activities in Taiwan †

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† Presented at the 4th International Electronic Conference on Atmospheric Sciences, 16–31 July 2021; Available online: https://ecas2021.sciforum.net.

Abstract: Due to the impact of global warming and extreme weather events, outdoor human thermal comfort conditions become tougher and harder to mitigate, especially for pedestrian movement and exercises. In order to better understand the thermal environment and thermal comfort, especially for outdoor sports, the 2021 National Intercollegiate Athletic Games held in Tainan, southern Taiwan, in May was selected as the research target. Both on-site, real-time environmental monitoring data and the Taiwan Climate Change Projection Information and Adaptation Knowledge Platform (TCCIP)'s Taiwan ReAnalysis Downscaling data (TReAD) were applied to estimate the modified physiologically equivalent temperature (mPET), the mean radiant temperature (Tmrt), and the wet bulb globe temperature (WBGT) for members participating in the relevant activities. The focus of this study was to analyze the thermal performance of (1) the torch relay around Taiwan from 20 April to 8 May and (2) the scheduled planning games held at the track and field stadium, at the National Cheng Kung University (NCKU), Taiwan, from May 15 to May 18, 2021.

Keywords: hot-humid climate; 2021 Taiwan National Intercollegiate Athletic Games; torch relay around Taiwan; thermal comfort; mPET; Tmrt; WBGT; thermal risk assessment

Citation: Yu, S.-Y.; Matzarakis, A.; Lin, T.-P. A Study Regarding the Thermal Environment and Thermal Comfort during the 2021 National Intercollegiate Athletic Games and Related Activities in Taiwan. *Environ. Sci. Proc.* **2021**, *8*, 32. https://doi.org/10.3390/ecas2021-10334

Academic Editor: Anthony R. Lupo

Published: 22 June 2021

1. Introduction

With the unavoidable fact of global warming and the increasing frequency of high-temperature days causing outdoor thermal stress to rise, this could frequently cause us to feel hot and uncomfortable. The high-temperature outdoor environment may also cause thermal hazards, which not only affects the quality of life but also affects health and public safety. During athletic games or activities, volunteers and staff participating in the athletic games in the venue need to continue their work and stay in the fixed area for hours. Thermal hazards and thermal comfort issues in the outdoor environment are important concerns for human quality of life. Therefore, it is essential to find ways to better adjust and quantify the influence of thermal comfort and risk for significant athletic activities.

As they were affected by the COVID-19 global epidemic, most of the international athletic games and activities could not be held recently. Taiwan has benefited from a quick reaction to avoid from enhancing the COVID-19 pandemic condition and the full commitment of the central government and all nationals; it was lucky that we could hold the 2021 National Intercollegiate Athletic Games and related activities, such as the torch relay around Taiwan and preliminaries, held from the middle of April to early May. With comprehensive consideration of public health and the pandemic, the decision to postpone the track and field race planned for May 15–18 to this September was made on May 13. Since then, the track and field stadium has been closed to prevent people from gathering there, and thus, on-site environmental monitoring and questionnaires will not be able to be initiated until September.

Regarding the issue of outdoor thermal comfort, there are many factors involved [1–3], and it is also strongly dependent on individuals' places of residence and preferences for sunlight or shade. Shade and a lower sky view factor would be the top concerns in promoting thermal comfort adaptation, especially for sub-tropical/tropical climates [4–11]. The aim of this study was to apply the real-time monitoring data along with the Taiwan Climate Change Projection Information and Adaptation Knowledge Platform (TCCIP) Taiwan ReAnalysis Downscaling data (TReAD) at 2 km grid resolutions of different locations in Taiwan, and this was a preliminary study to investigate the implementation of simulating the thermal performance before scheduled events or activities in the future.

2. Methods

2.1. Study Area and Settings

In this study, research areas and periods were (1) the torch relay around Taiwan from April 20 to May 8, and (2) the scheduled games held at the track and field stadium, NCKU, Taiwan from May 15 to May 18. Regarding the former, 142 sites in 16 cities/counties, including 32 universities in and around Taiwan, were selected to connect the torch relay route, as shown in Figure 1a. The scheduled 5 turns for this 1164 km tour are shown in Figure 1b.

(**a**) (**b**)

Figure 1. The torch relay around Taiwan from April 19 to May 9: (**a**) the entire torch relay—142 sites and TReAD 2 km grids in Taiwan; (**b**) the scheduled 5 turns: ① Tainan City, Taitung County, 280 km, April 20–23, ② Taitung County, Yilan County, 229 km, April 23–27, ③ Yilan County, Taoyuan City, 196 km, April 27–May 1, ④ Taoyuan City, Nantou County, 276 km, May 1–5, and ⑤ Nantou County, Tainan City, 183 km, May 5–8.

Regarding the second research area and period—the scheduled games held from May 15 to May 18—the track and field stadium, NCKU, Taiwan, has been closed since the postponement announcement made on May 13. Three sites near the venue, shown in Figure 2, were selected as "open" and "shade" monitoring sites to estimate the outdoor thermal conditions for if the track and field games were held as planned.

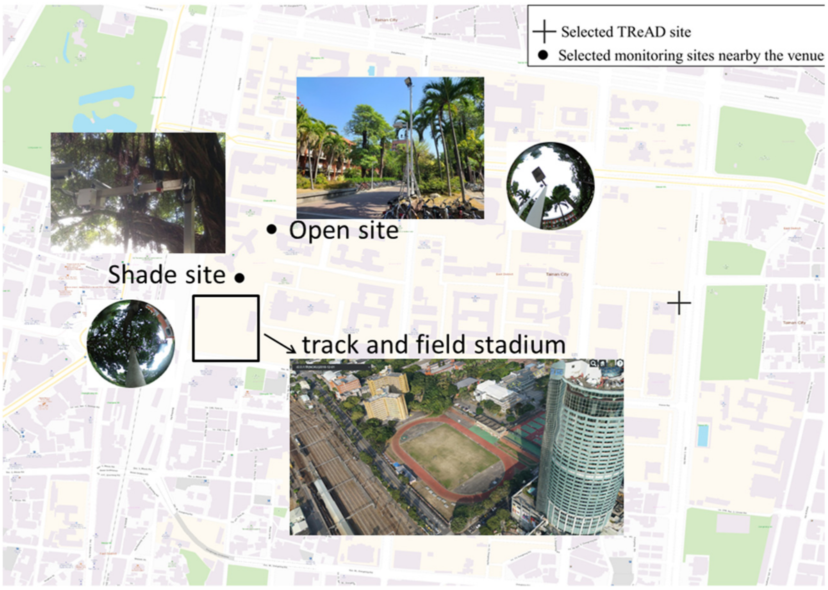
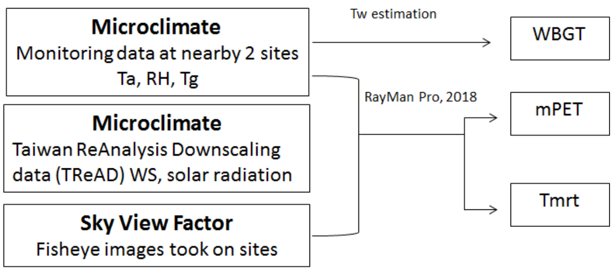


Figure 2. Open and shade monitoring sites and the TReAD 2 km grid area near the game venue.

The data applied and the process phases are summarized in Scheme 1. More details regarding the real-time monitoring of the data, the sky view factor, and the definition of thermal indices are described in Sections 2.2–2.4.



Scheme 1. Data application and analysis steps for Taiwan sites.

In this study, the modified physiologically equivalent temperature (mPET), instead of the PET, was applied to better determine the co-relationship between human biometeorological factors and thermal environments [12]. Nevertheless, the mean radiant temperature (Tmrt, the mean temperature of the surrounding surface of the environment radiating from the human body), and the wet bulb globe temperature (WBGT, a parameter for evaluating the environment thermal load of the human body) were also applied here as thermal indicators to gain a more comprehensive perspective.

As previously mentioned, places of residence and preferences play quite important roles in indicating thermal comfort. Hence, people from different regions have different thermal sensations and tolerance. The warm temperature for people in Taiwan is "PET 34–38 °C" while a PET > 38 °C would cause people to feel hot and very uncomfortable [13]. Assuming the condition of exposure under the direct solar radiation might cause the Tmrt to rise to 60 °C [14]. It was proved that once the body temperature is forced to increase to over 40 °C, there is a higher possibility of heatstroke and confusion [15]. The Japanese Ministry of the Environment and Japan Sports Association announced the guidelines for the WBGT standard of prevention of heat disorder [16–18]; when the WBGT is >25 °C, the heat stress risk increases and the "warning" level is reached, while a WBGT > 31 °C reaches the "danger" level, and exercise is prohibited.

Therefore, an mPET ≧ 34 °C and a WBGT > 25 °C were viewed as the thresholds for experiencing thermal discomfort; an mPET > 38 °C, a Tmrt ≧ 40 °C, and a WBGT > 31 °C were identified as the thresholds for thermal danger risk for people in this study.

2.2. Environmental Data Applied

For the scheduled games held at the track and field stadium from May 15 to May 18, UnaSense sensors from UnaBiz SigFox were used to monitor the air temperature (detection range of −20~70 °C, with ±1 °C accuracy) and relative humidity (detection range of 0~100%, with ±2% RH accuracy). Temphawk sensors (detection temperature range of −40 to 125 °C, with ±0.2 °C accuracy; detection relative humidity range of 0~100%, with ±3% RH accuracy), covered with small copper balls and dyed black, were used to monitor the globe temperature (Tg) shown as Figure 3.

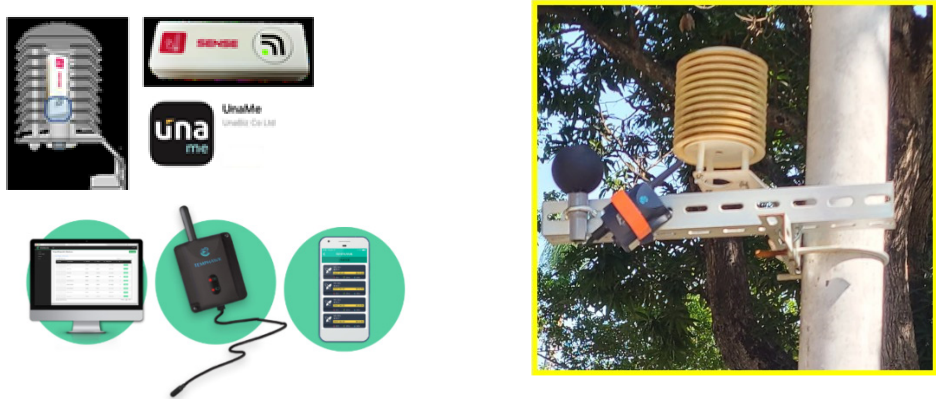


Figure 3. UnaSense (**left top**) and Temphawk (**left bottom**) sensors and installation.

For the torch relay around Taiwan from April 20 to May 8, the coverage area was the whole island, and there was the inevitable problem of a lack of sites providing sufficient data with a similar quality assurance/quality control process. Therefore, the Taiwan Climate Change Projection Information and Adaptation Knowledge Platform (TCCIP) Taiwan ReAnalysis Downscaling data (TReAD) were applied in this study for estimating the thermal performance along the torch relay route.

The TReAD was created via dynamic downscaling for obtaining high-resolution data by enhancing the resolution of the model. By applying terrain data near to the ground, it produced more accurate and realistic estimated data, which better presented geographical and climatic characteristics in small scales, and also allowed the model to simulate larger extreme values and could enlarge the model capacity to simulate extreme events. These data were reanalyzed ERA5 data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) using the WRF model. The original resolution was reduced to 30 km through dynamic downscaling, and then the ERA5 reanalysis data was gradually downscaled to 2 km grid [19–21]. There were approximately 15,000 dots around the island.

In this study, the reanalyzed and downscaled mean TReAD 2011–2018 hourly 2 km resolution data of near-the-ground air temperature (Ta), relative humidity (RH), wind speed (WS), and solar radiation (Sol) were applied. As an example used in this study, 5 torch relay sites in Taipei, along with 4 nearby TReAD sites were selected and they are shown in Figure 4. The arrival times for sites A to E were May 1 at 8:00, 9:00, 10:00, 11:00, and 12:00 in the morning, respectively. The sky view factor (SVF) was estimated at 142 sites via GSV2SVF—an interactive GIS tool that transforms Google Street View (GSV) images into fisheye images. With fisheye images, we were able to estimate the sky, tree, and building view factors [22,23]. The SVFs, TVFs, and BVFs along the torch relay route around Taiwan are shown in Figure 5. The data application and analysis steps for the Taipei site thermal indicator estimations are shown in Scheme 2.

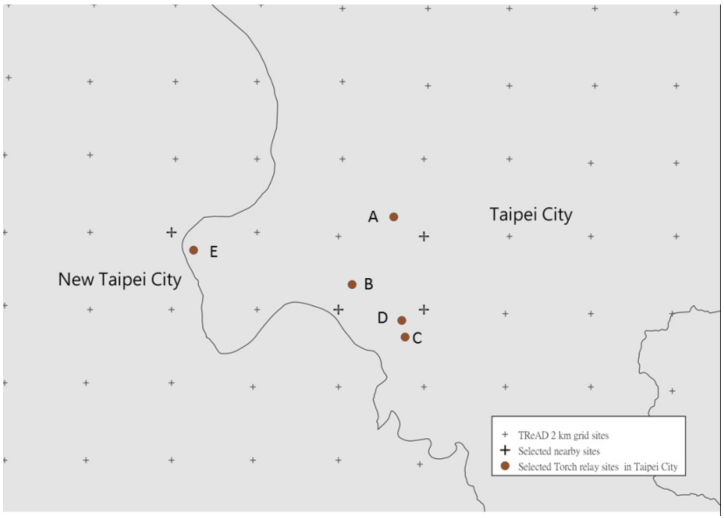
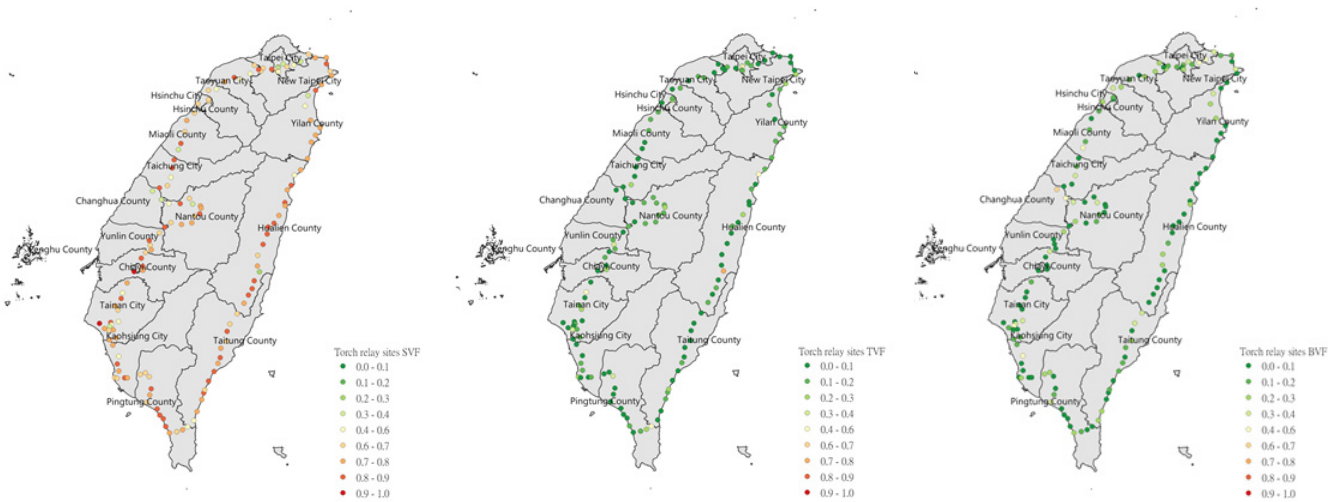
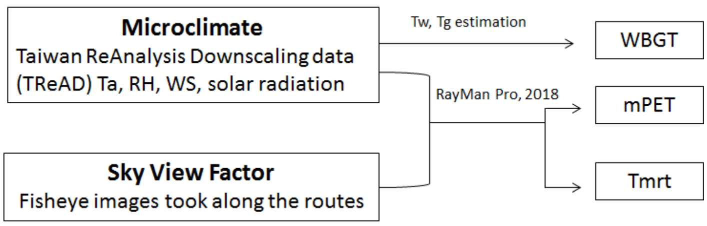


Figure 4. Selected torch relay sites in Taipei and the TReAD 2 km grid points nearby.



(**a**) (**b**) (**c**)

Figure 5. (**a**) SVFs, (**b**) TVFs, and (**c**) BVFs along the torch relay route around Taiwan.



Scheme 2. Data application and analysis steps for Taipei sites.

2.3. Wet Bulb Globe Temperature (WBGT) Estimation

The WBGT is an estimation to quantify the heat stress under a constant direct sunlight environment by ISO 7243 [24] in outdoor solar exposure conditions, expressed as the following equation:

$$\mathrm{WBGT} = 0.7\mathrm{Tw} + 0.2\mathrm{Tg} + 0.1\mathrm{Td} \tag{1}$$

where Tw is the wet bulb temperature, Tg is the globe temperature, and Td is the dry bulb temperature.

The method and function for estimating the Tg for southern Taiwan was developed by [11,25], and was applied to estimate the WBGT in this study, as follows:

$$Tg = Ta + (sol-14.91974)/(0.07796*sol + 12.83756*wind + 16.89265) \quad (2)$$

where Tg is the globe temperature, Ta is the air temperature, sol is the solar radiation, and wind is the wind velocity.

2.4. mPET and Tmrt Estimation

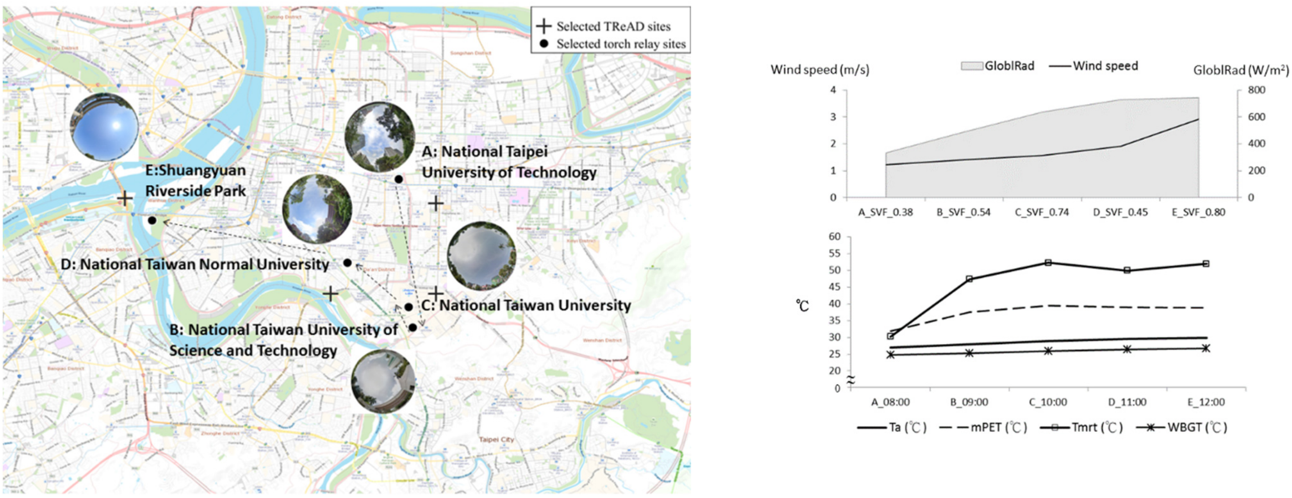
For the scheduled games held at the track and field stadium, NCKU, Taiwan from May 15 to May 18, by providing the real-time air temperature, relative humidity, and the SVFs from the 2 sites; and the reanalyzed TReAD wind speed and global radiation data from the nearest point less than 1 km away from the venue were applied. Then RayMan pro model was used in this study to estimate the mPET and Tmrt [26,27].

According to the Annex B metabolic rates of different activities in ISO 7730 [28], in the study, the initial condition settings for (1) the torch relay participants, as "runners" were defined as slow runners who would complete a 10 km route within 2 h at a rate of 5 km/h and a metabolic rate of 200 W/m^2, and (2) volunteers and staff participating in the athletic games as "standing or slow walkers" were expected to stay longer at the venue with relatively slower pedestrian movements with a moving rate of 2–2.5 km/h and a metabolic rate of 110 W/m^2. As for clothing, in order to focus primarily on the thermal environment in this study, a daily wear clothing option of underwear, shirt, trousers, socks, and shoes with a clothing insulation (Icl) value of 0.7 clo was generally applied in this study [29–31].

3. Results and Discussion

3.1. The Selected Five Torch Relay Sites in Taipei at 8 A.M. to 12 P.M. on May 1

For the analysis, five torch relay sites in Taipei, along with four nearby TReAD sites were selected. The fisheye photos and the map of the torch relay sites in Taipei and the thermal performance at 8 a.m. to 12 p.m. on May 1 are shown in Figure 6 and Table 1.



(**a**) (**b**)

Figure 6. (**a**) The fisheye photos and the map of the 5 torch relay sites in Taipei, and (**b**) the torch relay thermal performance at 8 a.m. to 12 p.m. on May 1.

Table 1. The torch relay risk of thermal discomfort from 8 a.m. to 12 p.m. on May 1.

Thermal Thresholds	Risk Percentage	Standards
mPET > 34 °C	80.0%	Warm standard for Taiwan [a]
mPET > 38 °C	80.0%	Hot standard for Taiwan [a]
Tmrt > 40 °C	80.0%	
WBGT > 25 °C	80.0%	Warning standard [b]
WBGT > 31 °C	0	Danger standard [b]

[a] Lin and Mazarakis [13], [b] Ministry of the Environment, Japan [16].

As seen in Figure 6b, the solar radiation gradually increased from 330 W/m^2 at 8 a.m. to 740 W/m^2 at noon. The SVFs of the five sites were estimated to be between 0.38 and 0.80. The Ta, mPET, and WBGT were quite steady, and the rise tendency, along with the increase in solar radiation reaching the ground over time, was not obvious. While the Tmrt had a relatively clear increasing trend over time, the highest Tmrt point was 52.2 °C. With higher solar radiation heat occurring by noon, the mPET and Tmrt values at 12 p.m. were even lower than previously. This could have been related to the better ventilation conditions (a higher wind speed).

As seen in Table 1, the risk for experiencing thermal discomfort was 80% for an mPET > 34 °C (warm standard for Taiwan), an mPET > 38 °C (hot standard for Taiwan), a Tmrt > 40 °C, a WBGT > 25 °C (warning standard for outdoor exercises), and a WBGT > 31 °C (danger standard for exercise), which indicates that all sites at the route in the morning were determined to very likely have thermal discomfort or heat stress hazards after 9 a.m.

3.2. The Scheduled Games Held at the Track and Field Stadium, May 15–18

As the track and field stadium has been closed since the postponement announcement made on May 13, two sites near the venue, representing an open area and a tree-shaded area, were selected as replacements for on-site monitoring of the track and field stadium to estimate the outdoor thermal conditions for if the games were held as scheduled. The thermal performances of the selected open and the shade sites nearby the venue during the scheduled game period are shown in Figures 7 and 8.

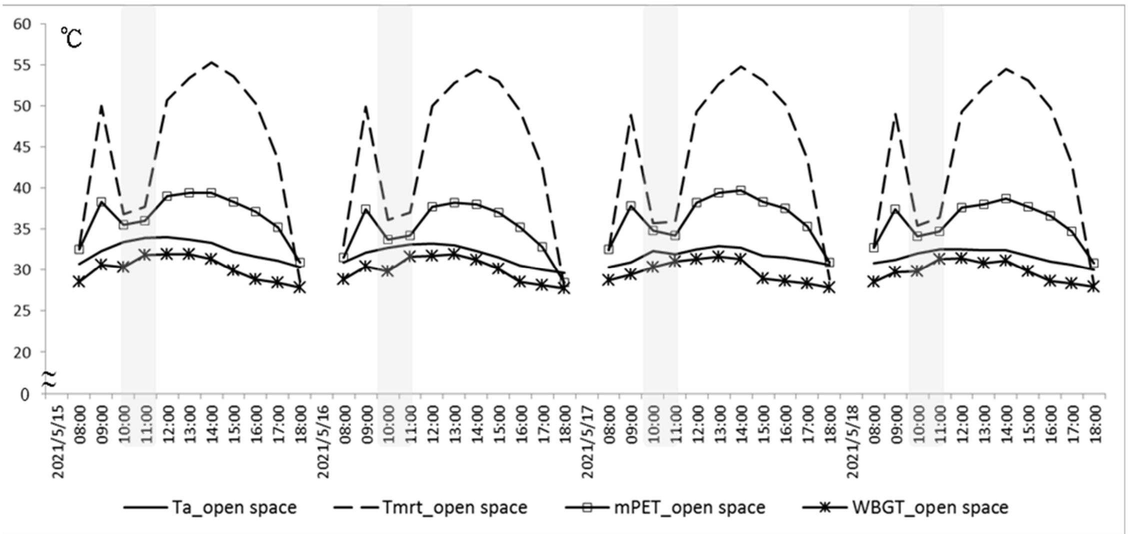


Figure 7. The open site thermal performance nearby the track and field stadium, NCKU, May 15–18.

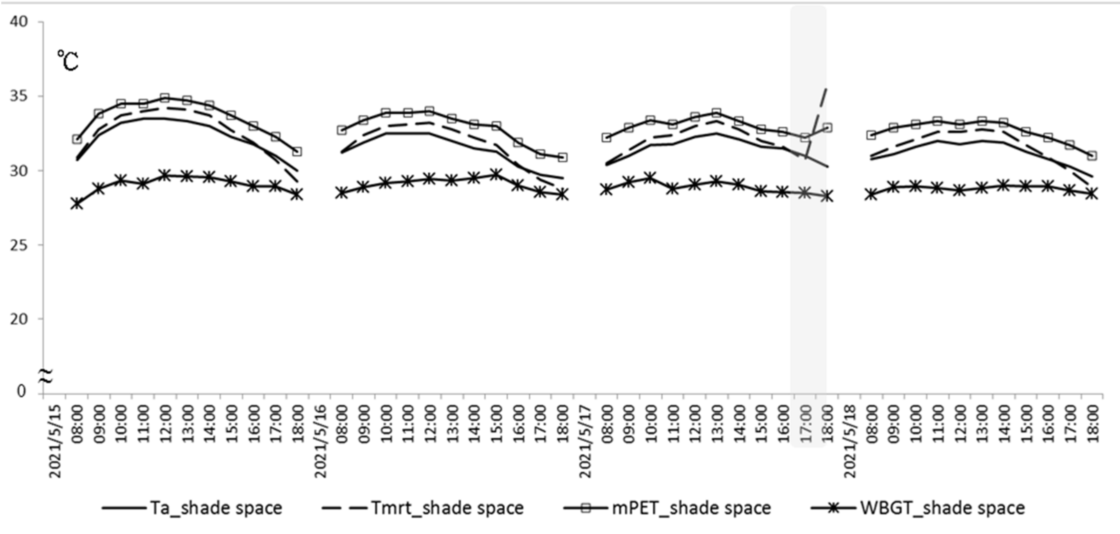


Figure 8. The shade site thermal performance nearby the track and field stadium, NCKU, May 15–18.

As seen in Figure 7, there were repeated low values for the Tmrt and mPET from 10 a.m. to 11 a.m. After comparing the solar track in the sky and the fisheye photos, we found the reason for this was that the structure of the LED street light caused sufficient shade as a shield at 10–11 a.m., affecting the sensors installed beneath it. The peak for the thermal indices occurred at 2 p.m., and the values were higher in the afternoon for the Tmrt and mPET, and at around noon for the WBGT. The Tmrt, mPET, and WBGT reached up to >50 °C, >39 °C, and >31 °C from 11 a.m. to 3 p.m.

As seen in Table 2, the risk values for experiencing thermal discomfort were 77.3%, 31.8%, 63.6%, 100.0%, and 34.1% for an mPET > 34 °C (warm standard for Taiwan), an mPET > 38 °C (hot standard for Taiwan), a Tmrt > 40 °C, a WBGT > 25 °C (warning standard for outdoor exercises), and a WBGT > 31 °C (danger standard for exercise), which indicates that if one had stayed in the open area without proper shading, there would have been a risk of experiencing heat stress the entire time, and for around one-third of the time, the situation would have been considered to be too hot and dangerous.

Table 2. The open site risk for experiencing thermal discomfort, May 15–18.

Thermal Thresholds	Risk Percentage	Standards
mPET > 34 °C	77.3%	Warm standard for Taiwan [a]
mPET > 38 °C	31.8%	Hot standard for Taiwan [a]
Tmrt > 40 °C	63.6%	
WBGT > 25 °C	100.0%	Warning standard [b]
WBGT > 31 °C	34.1%	Danger standard [b]

[a] Lin and Mazarakis [13]; [b] Ministry of the Environment, Japan [16].

As seen in Figure 8, the peak values under tree shade occurred at 12 p.m. for the Tmrt, mPET, and Ta on May 15 and 16, and shifted to 1 p.m. for the following two days. The WBGT trend did not present similar distribution characteristics as the other thermal indices nor the air temperature. The WBGT values were quite steady during the monitored period of time, and the peaks occurred at 3 p.m. and 10 a.m. on May 16 and 17, as opposed to at around noon. The mPET and Tmrt declined after 2 p.m., and the Tmrt tended to be lower than the air temperature after 4 p.m., but the mPET and Tmrt values suddenly rose to 32.9 °C and 35.8 °C on May 17 at 6 p.m.

As seen in Table 3, the shade site risk values for experiencing thermal discomfort were 13.6% and 100.0% for an mPET > 34 °C (warm standard for Taiwan) and a WBGT > 25 °C (warning standard for outdoor exercises), respectively, which indicates that if one had stayed under the tree shade area, there would have been a slight chance of feeling thermal discomfort for the duration of the event, but it would not have been too hot or too uncomfortable for the majority of the time.

Table 3. The shade site risk for experiencing thermal discomfort, May 15–18.

Thermal Thresholds	Risk Percentage	Standards
mPET > 34 °C	13.6%	Warm standard for Taiwan [a]
mPET > 38 °C	0.0	Hot standard for Taiwan [a]
Tmrt > 40 °C	0.0	
WBGT > 25 °C	100.0%	Warning standard [b]
WBGT > 31 °C	0.0	Danger standard [b]

[a] Lin and Mazarakis [13], [b] Ministry of the Environment, Japan [16].

The temperature differences between the open site and the shade site (T_{open}—T_{shade}) are shown in Table 4, indicating how much cooler shade could keep the area. Checking the temperature differences between thermal indices and air temperature indicated that the shade could very effectively lower the heat, especially from 11 a.m. to 2 p.m. The shade could keep the Tmrt, the mPET, the WBGT, and the Ta a total of 22.2 °C, 6.4 °C, 2.7 °C, and 1.0 °C lower, respectively, than the conditions without proper shading.

Table 4. The temperature difference between open site and shade site (T_{open}—T_{shade}).

2021/5/15	△Ta	△Tmrt	△mPET	△WBGT	2021/5/17	△Ta	△Tmrt	△mPET	△WBGT
08:00	0.0	1.9	0.4	0.7	08:00	−0.1	1.9	0.3	0.0
09:00	−0.1	17.2	4.5	1.8	09:00	−0.1	17.5	4.9	0.2
10:00	0.2	3.1	1.0	1.0	10:00	0.6	3.5	1.4	0.8
11:00	0.4	3.7	1.5	2.7	11:00	0.1	3.5	1.1	2.2
12:00	0.5	16.5	4.1	2.3	12:00	0.2	16.3	4.6	2.3
13:00	0.4	19.3	4.7	2.3	13:00	0.4	19.4	5.5	2.3
14:00	0.3	21.6	5.0	1.8	14:00	0.6	22.0	6.4	2.3
15:00	−0.1	20.9	4.6	0.7	15:00	0.1	21.1	5.5	0.4
16:00	−0.2	18.4	4.1	−0.1	16:00	0.0	18.6	4.9	0.1
17:00	0.1	12.8	2.9	−0.6	17:00	0.1	12.8	3.1	−0.1
18:00	0.3	−0.8	−0.4	−0.5	18:00	0.3	−7.0	−2.0	−0.4
2021/5/16	△Ta	△Tmrt	△mPET	△WBGT	2021/5/18	△Ta	△Tmrt	△mPET	△WBGT
08:00	−0.3	1.7	−1.2	0.3	08:00	0.0	1.9	0.3	0.1
09:00	0.2	17.5	4.0	1.5	09:00	0.1	17.5	4.5	0.8
10:00	0.2	3.1	−0.2	0.7	10:00	0.4	3.3	1.0	0.9
11:00	0.6	3.9	0.3	2.4	11:00	0.5	3.8	1.4	2.5
12:00	0.7	16.8	3.7	2.3	12:00	0.7	16.7	4.5	2.7
13:00	1.0	20.0	4.7	2.5	13:00	0.4	19.5	4.7	2.0
14:00	0.8	22.2	4.9	1.7	14:00	0.5	21.9	5.5	2.2
15:00	0.2	21.3	4.0	0.4	15:00	0.4	21.4	5.1	0.9
16:00	0.2	19.0	3.3	−0.5	16:00	0.2	18.9	4.4	−0.3
17:00	0.3	13.1	1.7	−0.4	17:00	0.3	13.0	3.0	−0.3
18:00	0.1	−1.0	−2.5	−0.7	18:00	0.4	−0.7	−0.2	−0.5

4. Conclusions

Even though the 2021 National Intercollegiate Athletic Games track and field race scheduled for May 15 to 18 had to be postponed to September due to public health concerns regarding COVID-19, by analyzing the thermal conditions near the venue, we determined there was a relatively high risk for experiencing heat stress and thermal discomfort while staying outdoors without shading during the previously scheduled game period. The outdoor conditions are expected to be milder this September, so it could also be beneficial for all of the game participants to have a safer and more comfortable experience. On-site environmental monitoring and the questionnaire will be carried out this September.

For analyzing an area that is wide or lacking in sites that provide a sufficient data set with a similar quality assurance/quality control process, reanalyzing and downscaling the data could be quite helpful. However, there is still a need to understand how to adjust the simulated data accuracy to be closer to the real conditions near the surface, such as the wind speed and solar radiation data since these conditions could be affected by various factors detected only at a street scale, and the value could rapidly change in short periods of time. In this study, only five sites in Taipei out of 142 sites along the torch relay route around Taiwan were selected to analyze the thermal conditions for investigating the implementation of applying TReAD reanalysis downscaling simulation data, the GSV2SVF tool, and RayMan pro. It is quite certain that the analysis of all 142 sites will be continued in the near future, and the study of the variations among the SVFs, TVFs, and BVFs at different urban areas in Taiwan will be also continued.

Author Contributions: Conceptualization and methodology, S.-Y.Y., T.-P.L. and A.M.; formal analysis and investigation, S.-Y.Y.; writing—original draft preparation, S.-Y.Y.; writing—review and editing, S.-Y.Y., T.-P.L. and A.M. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors greatly appreciate the support, and data sharing from the Taiwan Climate Change Projection Information and Ad aptation Knowledge Platform (TCCIP) Taiwan ReAnalysis Downscaling data (TReAD), Ministry of Science and Technology (MOST), and National Science and Technology Center for Disaster Reduction (NCDR), Taiwan.

Conflicts of Interest: The authors declare no conflict of interest.

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