

Article

Influence of Weather Factors on Thermal Comfort in Subtropical Urban Environments

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Abstract: Urbanization has influenced the distribution of heat in urban environments. The mutual influence between weather factors and urban forms created by dense buildings intensify human perception of the deteriorating thermal environment in subtropics. Past studies have used real-world measurements and theoretical simulations to understand the relationship between climate factors and the urban heat island effect. However, few studies have examined how weather factors and urban forms are connected to the thermal environment. To understand the influence of various weather factors on urban thermal environments in various urban forms, this study applied structural equation modeling to assumptions of linear relationships and used quantitative statistical analysis of weather data as well as structural conversion of this data to establish the structural relationships between variables. Our objective was to examine the relationships among urban forms, weather factors, and thermal comfort. Our results indicate that weather factors do indeed exert influence on thermal comfort in urban environments. In addition, the thermal comfort of urban thermal environments varies with location and building density. In hot and humid environments in the subtropics, humidity and wind speed have an even more profound impact on the thermal environment. Apparent temperature can be used to examine differences in thermal comfort and urban forms. This study also proved that an urban wind field can effectively mitigate the urban heat island effect. Ventilation driven by wind and thermal buoyancy can dissipate heat islands and take the heat away from urban areas.

Keywords: Structural equation modeling; subtropics; urban thermal environment; urban form; thermal comfort

1. Introduction

The increasing urbanization of the subtropics is producing expanding urban areas with high density and a growing number of tall buildings [1]. The reduction of natural scenery and the proliferation of human-made buildings and pavement are increasing the temperatures of urban environments [2] and the heat storage capacity of buildings and the ground [3], thereby magnifying the urban heat island effect. This effect is a unique phenomenon in terms of temperature distribution and distinguishes urban environments from rural ones in terms of temperature research [4–6]. Urban heat islands show a direct correlation between land cover and human use of energy [7]. As urban temperatures rise, the demand for energy increases, severely affecting human comfort [8–11]. Over the past century, the island of Taiwan has seen an increase in temperature (1.0–1.4 °C/100 years) [12]. Under the impact of global warming and the urban heat island effect, the average and minimum temperatures in Taipei have risen significantly [13,14]. Summers in the subtropics cause thermal discomfort, particularly in highly-urbanized areas, where urban heat island effects increase this discomfort [15]. In low-latitude regions, the rate at which it heats up in the summer is even higher [13], so research on the urban heat island effect in the tropics is becoming increasingly important [16].

As climate change enhances the severity of the urban heat island effect, the impact of outdoor weather conditions on comfort is becoming more profound [17–20]. During urban planning processes, the urban heat island effect and outdoor comfort are crucial issues in need of review and research [21–23]. Factors which affect outdoor environments are multiple, and in microclimates, meteorological variables may vary substantially with time and space [22]. The elements of a thermal environment include air temperature, humidity, thermal radiation, and air velocity. Research has shown that thermal comfort is affected not only by air temperature but also by the combined effects of air velocity, humidity, and solar radiation [24–26]. Fanger [27] mentioned that various physical factors in urban areas exert an impact on human comfort. Thus, research on thermal comfort cannot merely involve discussions of temperature [28–30].

Human comfort is established on the exchange of heat between humans and the surrounding environment, so an increasing number of studies are examining the influence of urban climate factors on human comfort from different perspectives. Common indices that have been used in research on outdoor comfort can be divided into rational indices and empirical indices [31], including predicted mean vote (PMV), standard effective temperature (SET), physiological equivalent temperature (PET), and the universal thermal climate index (UTCI). The PMV and SET indices have a solid foundation in research into indoor comfort, whereas the PET and UTCI were designed for outdoor use [32].

The calculation method for apparent temperature (AT) is generally suitable for the outdoors and is defined as the temperature perceived by the human body from the combined effects of ambient temperature, humidity, and solar radiation [33,34]. AT considers the effects of air temperature, relative humidity, and wind speed and is a suitable comfort index for climates with high temperatures and humidity. It is also currently used by the Central Weather Bureau in Taiwan. Although these physiological thermal comfort models are useful tools in research on outdoor thermal comfort, many researchers have discovered differences in their applications in different regions [35,36].

The factors that influence urban thermal environments are complex. The urban physical environment is an important field domain for human activities. Outdoor environmental factors could further affect the comfort in indoor environment. In urban climatology, researchers focus on how the climate of the surrounding environment alters its human perception rather than simply examining weather conditions such as temperature and precipitation [37]. The weather data from several weather stations is not enough to accurately evaluate climate conditions or give an understanding of the relationships between the urban environment and urban climate factors [38]. The urban heat island effect indicates that the temperature differences between environments are not only caused by natural climate conditions but are also caused by different building environments and urban forms [39].

Taiwan is situated in the subtropics, and its hot and humid climate is not simply the result of heat; its climate environment contains a combination of higher temperatures and humidity compared to other climate zones, so the urban outdoor environments are particularly hot, especially at noon and in the afternoon [40]. We conducted a case study using the weather data from the weather stations in Taipei, Taiwan, over one year and employed a structural equation model (SEM) to examine the extent to which different urban forms and weather factors influence one another. We analyzed this data to determine the influence of urban forms and their resulting thermal environments on comfort.

2. Materials and Methods

This study investigated whether the thermal environment is influenced by urban forms and weather factors using big-data analysis. We first used summer weather data to analyze weather factors and their influence on the urban thermal environment. An independent t-test identified the more influential weather conditions, which were then verified using year-round data and SEM statistical methods. Assumptions of linear relationships in the model were used to construct the structural relationships between variables, examine the relationships and influence among urban forms, weather factors, and thermal comfort, and analyze the urban forms of buildings surrounding the weather

stations. This study focuses on the urban environment. It is very informative by using the linear regression model through big data.

2.1. Study Area and Climate Conditions

Taipei City (25°05'N, 121°33'E), in Taiwan, is situated within a subtropical basin. Daily average maximum temperatures in July and August exceed 30 °C, and daily average relative humidity in the summer is over 80%. Aside from the weather stations belonging to the Central Weather Bureau, the elementary and junior high schools within the jurisdiction of Taipei City form the Taipei Weather Inquiry-based learning Network (TWIN). As a result, there is a weather station every 4.5 km on average, which makes Taipei City rich in resources for weather investigations. The study has applied for and is based on “Data bank for atmospheric & hydrologic research” [41] on TWIN [42], and there are 78 weather stations in Taipei City. We therefore adopted Taipei City area as our study area.

2.2. Weather Data Collection and Calculation Formulas

2.2.1. Compilation of Weather Data

The research data of this study comprised hourly weather data from June 2015, to May 2016. The weather data factors observed by the weather stations varied slightly with their level. The weather factors observed by the weather stations included air pressure, temperature, humidity, wind speed, wind direction, and rainfall. Cloud cover is observed manually, so only three weather stations had cloud cover and vapor pressure records.

2.2.2. Selection of Weather Stations

We included data from the weather stations belonging to the Central Weather Bureau and those in the elementary and junior high schools of Taipei City in our samples (Figure 1). Weather stations with too many missing values were eliminated. We calibrated the remaining data and filled in the missing values before data compilation and analysis. On average, each weather station provided a total of 8784 items of hourly weather data over the year, accounting for a total of 351,360 h, during which each item included air pressure, temperature, humidity, wind speed, wind direction, rainfall, etc. The weather data met the criteria for large samples in quantitative research.

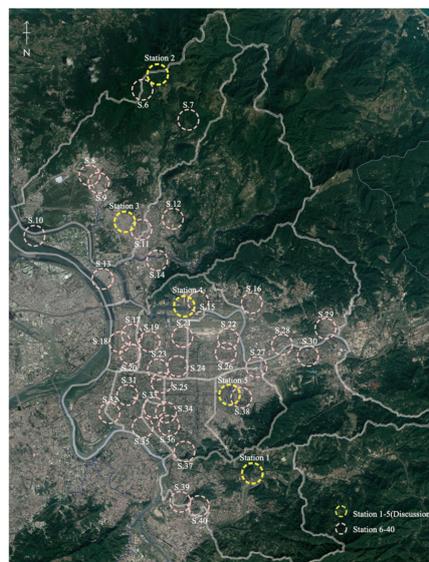


Figure 1. Weather stations and urban forms in study area.

2.2.3. Filling in the Missing Weather Data

In investigating the influence of different urban forms and weather factors on urban thermal environments, completeness in data collection is essential. Missing values may exist due to poor weather or mechanical malfunctions. We therefore filled in the missing values as follows:

For the missing values of average wind direction, we used the same wind direction data of the previous day. Linear interpolation based on the terms before and after the missing values was employed for temperature, humidity, rainfall, wind speed, and air pressure. The missing values of cloud cover were also calculated using linear interpolation. The calculation formula of linear interpolation was as follows [43]:

$$y = [(y - y_1)/(x_2 - x_1)](x - x_1) + y_1. \quad (1)$$

2.2.4. Calibration of Weather Data

Environmental conditions impact temperature [13]. Taipei City is situated in a basin with flat terrain in the middle and mountains surrounding it. Thus, some of the weather stations were at higher altitudes. Generally speaking, the temperature drops 0.6 °C for every hundred-meter increase in altitude. A small number of the weather stations in our study area were located in mountainous areas. To discuss the data from the weather stations under similar environmental conditions, we needed to calibrate the temperature data to minimize the impact of environmental conditions. We calibrated the temperatures to those that would have been derived had the weather stations been at an altitude of 0 m. Based on the temperature lapse rate, the temperature calibration formula was as follows:

$$\text{Temperature}' = \text{Temperature} + (\text{weather station altitude (m)}/100 \times 0.6), \quad (2)$$

2.2.5. Apparent Temperature Formula and Comfort Range

AT is the humidity-based temperature perceived by the human body. If the humidity is higher than the reference value, then the AT is higher than the dry-bulb temperature. If the humidity is lower than the reference value, then the AT is lower than the dry-bulb temperature. Humidity is a crucial factor in the hot and humid conditions in subtropical climate. The Central Weather Bureau in Taiwan provides ATs for public reference [33,34], so we included AT as one of the investigated indices in this study.

$$\text{Apparent temperature} = (1.04 \times \text{temperature}) + (0.2 \times \text{vapor pressure}) - (0.65 \times \text{wind speed}) - 2.7 \quad (3)$$

$$\text{Vapor pressure} = (\text{relativehumidity}/100) \times 6.105 \times \exp[((17.27 \times \text{temp.})/(237.7 + \text{temp.}))]$$

The Central Weather Bureau also describes the thermal sensations likely to accompany various AT ranges; these are presented in Table 1.

Table 1. Apparent temperature (AT) ranges of various thermal sensations in Taiwan (Central Weather Bureau).

Thermal Sensation	AT Range for Taiwan (°C AT)
Very cold	< 7
Cold	8–13
Cool	14–20
Comfortable	21–32
Hot	33–40
Susceptibility to heat stroke	< 40

2.2.6. Physiological Equivalent Temperature (PET) range for Thermal Comfort in Taiwan

The PET represents meteorological parameters that influence the balance of energy in the human body, such as air temperature, air humidity, wind speed, and long-wave and short-wave radiation. It also takes into account the thermal resistance of clothes and the generation of internal heat. T.-P. Lin and Matzarakis [44] modified the PET range for thermal comfort based on the results of 1644 outdoor interviews (see Table 2). The PET calculations were performed using the open-source software Rayman [45]. The PET is a thermal index derived from the energy balance in the human body. Its unit is °C, which makes it accessible for personnel unfamiliar with urban or regional planning [36].

Table 2. Physiological equivalent temperature (PET) range for thermal comfort in Taiwan [42].

Thermal Sensation	PET Range for Taiwan(°C PET)
Very cold	<14
Cold	14–18
Cool	18–22
Slightly cool	22–26
Neutral	26–30
Slightly warm	30–34
Warm	34–38
Hot	38–42
Very hot	< 42

2.2.7. Enthalpy Formula

Literature has shown that air temperature is too basic a measure for thermal comfort research. We therefore used the total enthalpy in air to investigate the distribution of heat in urban environments. Enthalpy was calculated using the following formula.

$$\text{Enthalpy} = C_p\theta + x(r + C_v\theta) \quad (4)$$

$$\theta = \text{air temperature (}^\circ\text{C)}$$

$$C_p = \text{specific heat of dry air at constant pressure, 1.005 (kJ/kg}\cdot\text{K)}$$

$$C_v = \text{specific heat of water vapor at constant pressure, 1.846 (kJ/kg}\cdot\text{K)}$$

$$X = \text{absolute humidity (kg/kg}'\text{'})$$

$$R = \text{latent heat of vaporization of water at } 0^\circ\text{C, 2501.1 (kJ/kg)}$$

2.3. Definition of Urban Forms and Visual Analysis

To identify the climate factor most related to the influence of urban forms on the thermal environment, we examined the buildings and land distributions surrounding the weather stations to discuss the relationship between urban forms and weather conditions. Urban form was determined based on the areas within 500 m of the weather stations. Relevant studies have indicated that this radius is enough to determine the influence of urban forms on air temperature [46].

We used the ArcGIS to combine graphic information from the digital terrain map of Taipei City, including the administrative area of Taipei City, road use conditions, various land use conditions, river channels and their basins, and architectural development within the city. The main elements of urban forms are building density and vegetation cover density.

$$\text{Building density} = (\text{Land area occupied by buildings/land area})\% \quad (5)$$

$$\text{Vegetation cover density} = (\text{Land area occupied by vegetation cover}/\text{land area})\% \quad (6)$$

2.4. Application of Structural Equation Modeling to Determine Influence of Urban Forms on Thermal Comfort

Before conducting SEM analysis, we first examined climate and environmental factors using statistical analysis to identify weather factors with more significant impact on the thermal environment of various urban forms. Then, we investigated the influence of urban form and weather factors on thermal comfort in urban environments using SEM analysis.

SEM analysis is a statistical technique commonly used by researchers of management control. It allows for analysis of the various important factors underlying the data. It further enables the researcher to determine whether the mutually associated dependent variables are dependent on one another [47,48]. SEM is also used in urban research to study the potential connections between urban landscapes and commercial layout characteristics [49]. Using SEM, we attempted to identify the most crucial factors that influence the thermal environments in subtropical cities under the same geographical and climate scenarios.

2.5. Statistical Operation

2.5.1. Preliminary Analysis of Weather Factors and Climate Scenarios and Patterns

The influence of the thermal environment in the subtropics on thermal comfort is most significant in the summer. To identify the weather factors with the most significant impact on urban thermal environments, we first analyzed summer data from weather stations in Taipei City, that is, data collected from June to August in 2015. In total, the samples covered 2208 h. The wind field and cloud cover data were analyzed using SPSS. In hypothesis testing, we used an independent t-test to verify the influence of the wind field and cloud cover factors on the urban thermal environment and conducted a post-hoc analysis of different cloud-cover groups. In 3.1.2, the linear relationships method is applied to discuss the differences between wind speed, cloud cover and climate scenarios and to classify the climate scenarios, and then to perform the calculation of the structural equation model. We investigated the influence of two climate scenarios on changes in the urban thermal environment: high radiative cooling effect and high greenhouse effect. These two climate scenarios have the most significant impacts on thermal comfort. Research [24–26] has shown that thermal comfort is affected not only by air temperature but also by the combined effects of air velocity, humidity, and solar radiation. So we have chosen these three factors as the linear regression model.

- Climate scenario categories

The temperature parameter cannot present thermal energy. For this reason, we used the enthalpy values of different climate scenarios in our verification. We categorized the weather data into two climate scenarios (high radiative cooling effect and high greenhouse effect) by eliminating time periods with high wind speeds and then dividing the weather data based on the amount of cloud cover. The climate scenario with a high radiative cooling effect involved low humidity and low-to-no cloud cover and formed Model 1, whereas the climate scenario with a high greenhouse effect involved high humidity and high cloud cover and formed Model 2.

- Influence of weather factors and climate scenarios

1. Wind field factor analysis

To understand the influence of wind field factors on the enthalpy in urban environments and reduce the impact of wind on climate patterns, we divided the weather data by wind speed and conducted an independent t-test with a control group made up of samples with wind speeds lower than 1.5 m/s.

$$H_0: \mu \text{ wind speed factor} = \mu \text{ wind speed } 1.5 \text{ m/s}$$

H_1 : μ wind speed factor \neq μ wind speed \leq 1.5 m/s

As shown in Table 3, $P = 0.156 > 0.05$ in the F-test, so the assumption of equal variances was not rejected. Also, $p = 0.000 < 0.05$, so the null hypothesis was rejected. These results show that wind speed has a significant impact on enthalpy in the urban environment.

Table 3. Independent t-test.

Enthalpy	Levene's Test or Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	Df	Sig. (two-tailed)	Mean difference	Std. error difference	95% confidence interval of difference	
								Lower	Upper
Equal variances assumed	2.013	0.156	8.794	2206	0.000	2.20866	0.25115	1.71614	2.70118
Equal variances not assumed			8.767	2125.616	0.000	2.20866	0.25193	1.71460	2.70272

2. Cloud cover factor analysis

Based on the results of the previous verification, we eliminated the data with wind speeds over 1.5 m/s, which resulted in a total of 1189 items of hourly data. To determine whether a significant correlation exists between enthalpy and cloud cover in urban environments, we divided the weather data by the amount of cloud cover. After eliminating 5 outliers, we obtained a total of 1184 items of hourly data (see Table 4).

Table 4. Numbers of outliers eliminated from each weather data group.

Group	Level of Cloud Cover	Total Items of Hourly Data	Outliers	Items of Hourly Data after Elimination
1	Levels 0–3	230	0	230
2	Levels 4–6	377	4	373
3	Levels 7–10	582	1	581
Total	-	1189	5	1184

We examined the differences among the groups using the Scheffé Test (see Table 5). Pairwise comparisons of different cloud cover levels and enthalpy values revealed significant results (p values < 0.05), thereby indicating that cloud cover indeed exerts a significant influence on enthalpy.

Table 5. Scheffé test.

(I) Cloud Cover Group	(J) Group	Mean Difference(I-J)	Std. error	Sig.	95% Confidence Interval	
					Lower	Upper
Group 1 (Cloud cover levels 0–3)	Group 2	−2.41831984 *	0.47456259	0.000	−3.5814038	−1.2552359
	Group 3	−1.30046709 *	0.44097262	0.013	−2.3812269	−0.2197073
Group 2 (Cloud cover levels 4–6)	Group 1	2.41831984 *	0.47456259	0.000	1.2552359	3.5814038
	Group 3	1.11785275 *	0.37556480	0.012	0.1973980	2.0383075
Group 3 (Cloud cover levels 7–10)	Group 1	1.30046709 *	0.44097262	0.013	0.2197073	2.3812269
	Group 2	−1.11785275 *	0.37556480	0.12	−2.0383075	−0.1973980

* This indicates that the mean difference is significant at the 0.05 level.

After verifying that differences indeed exist between different amounts of cloud cover, we conducted an independent sample t-test using Group 1 and 2 of the two climate scenarios, to verify the influence of cloud cover on the thermal environment. As shown in Table 6, $p = 0.881 > 0.05$ in the T-test, assuming equal variances, and $P = 0.004 < 0.05$ was significant. Thus, the results show that the influence of cloud cover on the thermal environment is significant, thereby indicating that the climate scenario affects the thermal environment.

Table 6. Independent t-test of cloud cover.

Enthalpy	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (two-tailed)	Mean difference	Std. error difference	95% confidence interval of difference	
								Lower	Upper
Equal variances assumed	0.022	0.881	-2.851	809	0.004	-1.30047	0.456074	-2.1958	-0.40524
Equal variances not assumed			-2.852	420.40	0.005	-1.30047	0.455968	-2.1967	-0.40421

- Influence of weather factors on thermal environments of different urban forms

We grouped the weather stations by building density. Those with building densities of 0–0.25, 0.26–0.5, 0.51–0.75, and 0.76–1 were categorized as Types 1, 2, 3, and 4, respectively. Type 1 represented the low density group, which contained a total of 6 weather stations. The remaining types formed the high density group, containing a total of 36 weather stations. Using an independent t-test, we determined whether building density exerted a significant impact on the urban thermal environment, the hypotheses of which were as follows:

H_0 : Building density has no impact on the enthalpy in the urban environment.

H_1 : $\mu_{\text{low building density}} = \mu_{\text{high building density}}$; μ denotes the average enthalpy in the urban thermal environment.

The Levene's test (Table 7) shows that the F statistic was $0.000 < 0.05$ and significant, so the assumption of equal variances in the two populations was not supported; $p = 0.497 > 0.05$, so H_0 was not rejected. Thus, in the climate environment in summer, no significant relationships exist between building density and enthalpy in the urban environment.

Table 7. Results of independent t-test.

Enthalpy	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (two-tailed)	Mean difference	Std. error difference	95% confidence interval of difference	
								Lower	Upper
Equal variances assumed	135.636	0.000	-1.270	502	0.205	-0.72871	0.57394	-1.85633	0.39890
Equal variances not assumed			-0.682	74.102	0.497	-0.72871	1.06786	-2.85642	1.39899

However, the 95% confidence interval of the difference still shows a connection between the enthalpy values of the two urban forms, namely, high building density and low building density. The 95% confidence interval of the difference obtained by subtracting the average enthalpy of low building density from that of high building density ranges from -2.85642 to 1.39899. The upper and lower limits are within normal range, and there is a 95% chance of obtaining a positive difference when subtracting the average enthalpy of low building density from that of high building density. From this, we can infer that the average enthalpy of high building density is greater than that of low building density.

- Summary

The results of the above analysis indicate that under different wind speed conditions, wind can carry away the enthalpy in the environment, thereby improving thermal comfort. In addition, cloud cover also exerted a significant impact on the thermal environment. The conversion of enthalpy shows that urban forms with higher building density contain more enthalpy than those with lower building density. This is also because the weather stations are located in different areas, and the circled areas represent different building densities. The analysis results indicate that geographical location also influences the climate environment of the urban area.

This investigation focused on the summer climate, so the sample attributes were similar and the differences presented by the factors were not significant. We therefore increased the sample size to include year-round data for SEM analysis. Based on the path structures, we derived the causal relationships among the factors.

2.5.2. Structural Conversion of Research Data

Prior to SEM, we performed structural conversion of the research data. The research data comprised three major categories: urban forms, weather factors, and thermal environment factors. As the data was collected hourly, there was a substantial amount of data. Thus, the data had to be simplified structurally. Scaling in SEM is generally conducted using a seven-point Likert scale [50]. After dividing the year into four seasons, we calculated the means of the various weather factors using identical time intervals and then conducted scaling based on the characteristics of each weather factor and their impact on the thermal environment. Below, we explain the structural conversion for each data category.

- Urban forms

We graded building density based on the percentage of area occupied by buildings. A higher density meant a higher grade (Table 8). Weather station location was graded by the altitude of the weather station. A higher altitude meant a lower grade (Table 8).

Table 8. Conversion table for urban forms.

Building Density	Grade	Weather Station Location	Grade
0%	1	0–25 m	7
1–10%	2	25–100 m	6
10–30%	3	100–200 m	4
30–40%	4	200–500 m	3
40–50%	5	500–1000 m	2
50–60%	6	Over 1000 m	1
Over 60%	7	-	-

- Weather factors

The temporal data of the weather data included month and time. We categorized the data by season, with a higher grade for hotter seasons (Table 9). Each 24-hour period was divided into four time intervals, with a higher grade for hotter intervals (Table 9).

Table 9. Conversion table for time data.

Months and Corresponding Season	Grade	Time Interval	Grade
December–February	Winter	00–05	1
March–May	Spring	06–11	5
June–August	Summer	12–17	7
September–November	Autumn	18–23	3

The weather factors included temperature, relative humidity, wind speed, wind direction, accumulated rainfall, air pressure, and cloud cover. We used the calibrated temperature data in the preliminary analysis of the weather factors and climate scenarios and patterns and the original temperature data in SEM. Based on the human perception of temperature, we calculated ATs and

then scaled the results (Table 10). Higher relative humidity was given a higher grade (Table 10), as was higher wind speed (Table 10). For accumulated rainfall, we used the measurements of daily accumulated precipitation provided by the Central Weather Bureau for scaling (Table 11). One standard atmosphere, equaling 1013 hPa, served as the demarcation point for scaling air pressure. Cloud cover was scaled according to Table 11. The climate patterns in Taiwan are generally cloudy, and the annual average cloud cover is never below 5. For this reason, the lowest grade for cloud cover began at 5, and more cloud cover meant a higher grade (Table 11).

Table 10. Conversion table for weather factors (1).

Apparent Temperature	Grade	Relative Humidity	Grade	Wind Speed (m/s)	Grade
Under 0 °C	1	60 ≥ 70%	2	0.0 ≤ 0.1	7
1–7 °C	2	70 ≥ 80%	3	0.1 ≤ 1.5	6
8–13 °C	3	80 ≥ 90%	5	1.5 ≤ 3.3	5
14–20 °C	4	90 ≥ 100%	6	3.3 ≤ 5.5	4
21–32 °C	5	100%	7	5.5 ≤ 10.7	3
33–40 °C	6	-	-	Over 10.7	1
Over 40 °C	7	-	-	-	-

Table 11. Conversion table for weather factors (2).

Average Accumulated Rainfall	Grade	Air Pressure	Grade	Cloud Cover	Grade
No rain	0 mm	Under 1013 hPa	1	5	3
Light rain	0 < 80 mm	Over 1013 hPa	7	6	4
Heavy rain	80 ≤ 200 mm	-	-	7–8	6
Extremely heavy rain	200 ≤ 350 mm	-	-	9	7
Torrential rain	350 ≤ 500 mm	-	-	-	-
Extremely torrential rain	Over 500 mm	-	-	-	-

- Thermal environment factors

The thermal environment factors were the factors that influence the subsequent thermal environment, including enthalpy and AT. We derived the latter from the original temperatures using thermal comfort and then converted the results to AT. The enthalpy values were calculated using ventilated conditions (Table 12).

Table 12. Conversion table for enthalpy.

Enthalpy Range for Thermal Comfort	Grade
Under 79 kJ/kg	1
Over 79 kJ/kg	7

There are no universal standards for quantifying large amounts of weather data, so we converted the structure of the data for quantitative statistical analysis. With the various weather factors as independent variables, we examined the data in different urban-form groups in the study area. We identified the weather factors with significant impact on the urban thermal environment to facilitate subsequent thermal comfort analysis.

3. Modeling and Discussion

3.1. Modeling

To understand the weather factors that influence the thermal environment of different urban forms in subtropical regions, we had to first compile the path diagram before SEM analysis to describe the mutual relationships among the variables. The SEM was divided into four constructs (Figure 2). With urban form as the latent variable, weather station location, building density, and vegetation cover density served as the manifest variables. With solar radiation as the latent variable, season, time period, and temperature were the manifest variables. With weather pattern as the latent variable, cloud cover, wind direction, accumulated rainfall, and air pressure were the manifest variables, and with the thermal environment as the latent variable, humidity, wind speed, and enthalpy were the manifest variables. The assumption of our SEM was that the urban form and climate scenario, including solar radiation and weather patterns, impact the urban thermal environment.

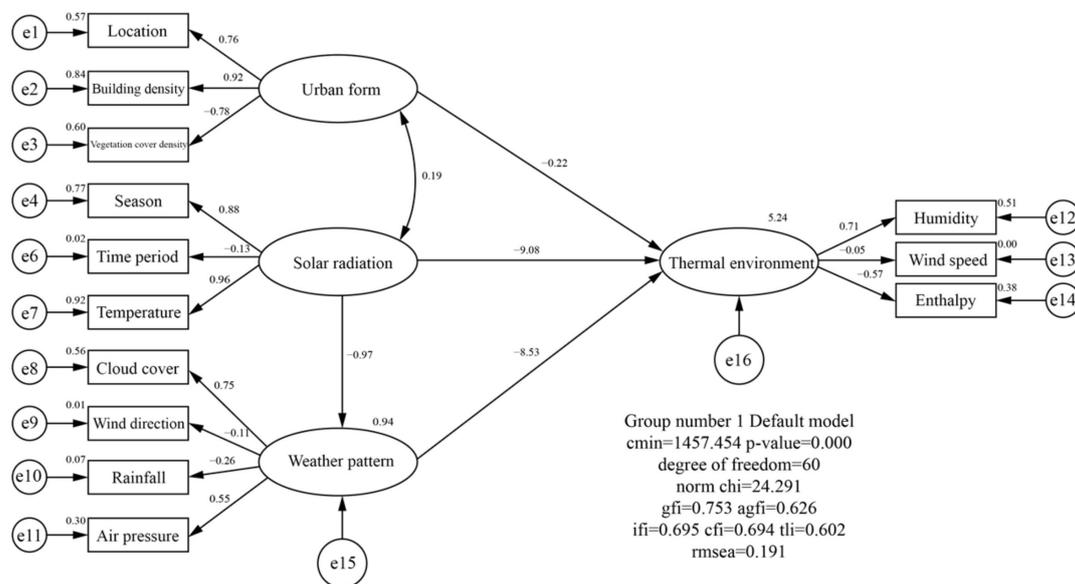


Figure 2. SEM analysis results of original concept diagram.

3.2. Analysis Results

3.2.1. Interpretation of SEM

We conducted SEM analysis using AMOS, the results of which are shown in Figure 2. The chi-square value was 1457.45, and the degree of freedom was 60. The P column in Table 13 shows whether the regression weights between the constructs in the model are significant, which indicates whether factor loadings exist. Each construct must have a factor set as 1 to serve as the reference index. Interpretation can only be made if all of the regression weights are significant. Those involving wind direction and wind speed were not significant, so these factors were removed from their constructs, and the analysis was performed again.

After the revisions, all of the regression weights were significant, so interpretations were made using the standardized factor loadings. Those greater than 0.6 were acceptable, those greater than 0.7 were ideal, and those less than 0.6 were eliminated. Table 13 presents the original variables and factor loadings, and Table 14 displays the remaining variables and factor loadings.

Table 13. Regression weights.

			Estimate	S.E.	C.R.	P	Label
Weather pattern	<—	Solar radiation	−0.454	0.020	−22.710	***	
Thermal environment	<—	Urban form	−0.116	0.018	−6.520	***	
Thermal environment	<—	Weather pattern	−6.888	5.615	−1.227	0.220	
Thermal environment	<—	Solar radiation	−3.436	2.565	−1.340	0.180	
Location	<—	Urban form	1.000				
Air pressure	<—	Weather pattern	1.462	0.096	15.187	***	
Building density	<—	Urban form	1.059	0.051	20.734	***	
Cloud cover	<—	Weather pattern	1.000				
Time period	<—	Solar radiation	0.135	0.040	3.353	***	
Season	<—	Solar radiation	1.000				
Vegetation cover density	<—	Urban form	−0.576	0.029	−19.566	***	
Wind direction	<—	Weather pattern	−0.116	0.039	−2.995	0.003	
Rainfall	<—	Weather pattern	−0.484	0.069	−7.034	***	
Humidity	<—	Thermal environment	1.000				
Wind speed	<—	Thermal environment	−0.033	0.028	−1.186	0.236	
Enthalpy	<—	Thermal environment	−1.444	0.096	−15.102	***	
Temperature	<—	Solar radiation	0.468	0.012	38.447	***	

***: significant

Table 14. Standardized regression weights.

			Estimate
Weather pattern	<—	Solar radiation	−1.019
Location	<—	Urban form	0.749
Air pressure	<—	Weather pattern	0.586
Building density	<—	Urban form	0.923
Cloud cover	<—	Weather pattern	0.728
Season	<—	Solar radiation	0.938
Vegetation cover density	<—	Urban form	−0.776
Rainfall	<—	Weather pattern	−0.236
Temperature	<—	Solar radiation	0.899

3.2.2. Analysis Results of Revised SEM

The previous SEM analysis results were poor, so we revised the model. Solar radiation and weather pattern were combined into a single construct, while the other constructs remained unchanged (Figure 3).

We then retested the significance of the regression weights of the revised model and eliminated the manifest indices of the factor loadings that were not ideal. The manifest index estimates in the weather pattern construct did not reach the ideal values, and after several tests, we eliminated the constructs that were not significant until only the urban form and thermal environment constructs remained in the revised SEM. The remaining variables were location, building density, humidity, and wind speed (Figure 4).

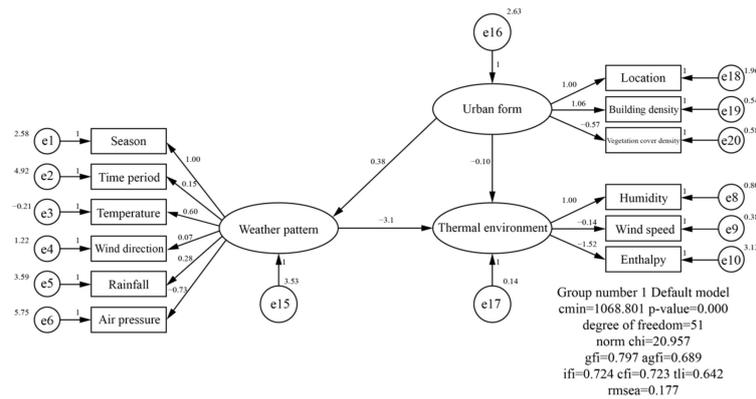


Figure 3. Revised path diagram 1.

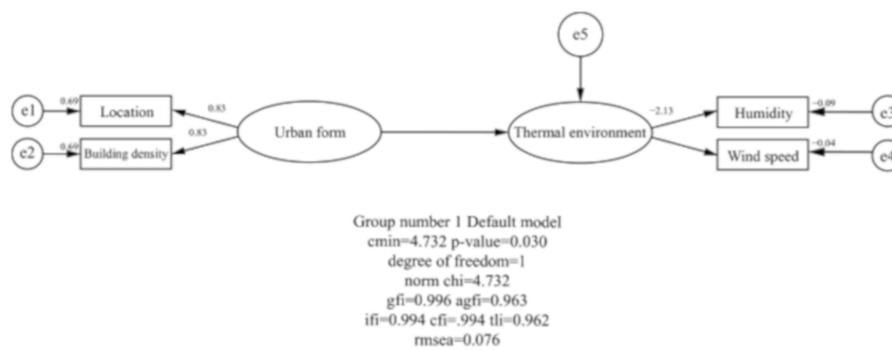


Figure 4. Revised path diagram 2.

3.2.3. Model Fit Analysis

Table 15 displays the various fit indices of the revised SEM, where the chi-square value (χ^2) was 4.732, the degree of freedom was 1, and $p = 0.030$. Among the relative fit indices, NFI, CFI, IFI, and RFI are greater than 0.95, which indicate that they are close to statistical standards and that the model fit is good. The SEM analysis results indicate that in terms of urban form, location and building density influence the thermal environment. In addition, the thermal environment is influenced by humidity and wind speed.

Table 15. Fit indices of model of influence of urban form on thermal environment.

Absolute Fit Index	Estimate	Relative Fit Index	Estimate	Parsimony Fit Index	Estimate
$\chi(1)$	4.732	NNFI	0.813	PNFI	0.165
GFI	0.996	NFI	0.992	PGFI	0.100
AGFI	0.963	CFI	0.994	χ^2/df	4.732
RMR	0.018	IFI	0.994		
RMSEA	0.076	RFI	0.953		
ECVI	0.036				

3.3. Urban Thermal Environment and Comfort Index Analysis

The SEM analysis results indicate that in urban form, location and building density influence the thermal environment and that among the weather factors, humidity and wind speed have the greatest impact on the thermal environment. These two factors are also crucial factors that influence the comfort index, AT. A humidity variable was also added to enthalpy calculations.

We thus selected weather stations with different locations, densities, and wind speeds for thermal comfort analysis. We then analyzed the ATs and the thermal comfort ranges in a psychrometric chart and compared the thermal comfort at weather stations with different urban forms to examine variations

in humidity and wind speed and their impact on the thermal environment. Table 16 compares the data of the different weather stations.

Table 16. Comparison table of weather stations.

Comparison	Weather Station	Building Density (%)	Altitude (m)	Average Wind Speed (m/s)
Location	Station 1	3.1%	72.57	0.26
	Station 2	0.4%	825.8	2.67
Density	Station 1	3.1%	72.57	0.26
	Station 3	76.2%	49	0.35
Wind speed	Station 4	56.6%	7	2.19
	Station 5	53.2%	71	0.35

3.3.1. Comparison of Temperatures and ATs Resulting from Different Urban Forms

- Different altitude locations

Stations 1 and 2 were chosen for comparison for their similar densities and different altitudes. However, the rugged terrain in mountainous areas means that the amount of solar radiation absorbed by the ground is uneven. This uneven heat distribution causes convective currents in the air, and with air movement encountering less resistance in mountainous areas, the winds become very strong [51]. We could not find any stations with similar wind speeds for comparison, so only Stations 1 and 2, which were located at significantly different altitudes, were compared.

Figure 5 compares the temperatures and ATs of the two stations. The temperatures measured at Station 2, which was located at a higher altitude, were significantly lower than those measured at Station 1, which was located at a lower altitude. The ATs measured at Station 2 were also lower than those measured at Station 1. After recalculating AT weighted with wind speed and humidity, we found the most significant differences at Station 1 during the period from 12:00 to 18:00 in the summer, where the difference between the AT and the original temperature reached 4.8 °C. The comparison graph revealed that the thermal environment of Station 1 was much hotter than that of Station 2. Furthermore, we found that in low-temperature conditions, the difference between the AT and the original temperature at the station 1 during the period from 00:00 to 6:00 in the winter reached −1.99 °C. ATs are higher in hot environments and lower in cold environments.

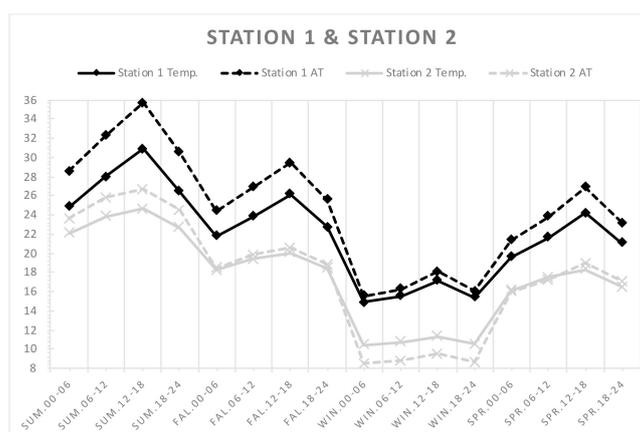


Figure 5. Comparison of temperatures and ATs at Stations 1 and 2.

- Different building densities

Stations 1 and 3 were chosen for comparison for their similar wind speeds and altitudes but different building densities. Figure 6 compares the temperatures and ATs of the two stations. As can be seen, the temperatures measured at Station 3, where the building density was 76.2%, were higher

than those measured at Station 1, where the building density was only 3.1%. The ATs of Station 3 were also higher than those of Station 1.

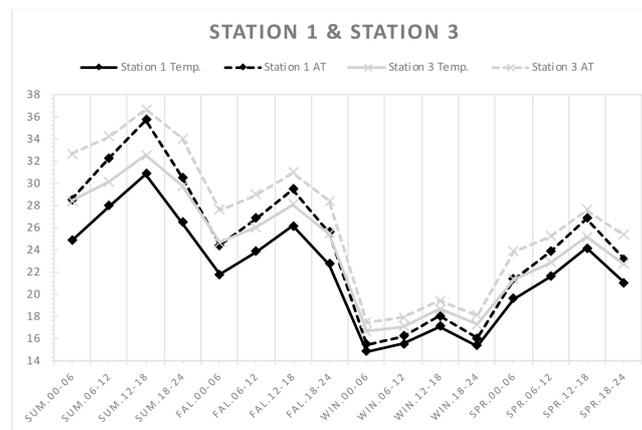


Figure 6. Comparison of temperatures and ATs at Stations 1 and 3.

3.3.2. Comparison of Temperatures and ATs Resulting from Different Weather Factors

- Different wind speeds

Stations 4 and 5 were chosen for comparison for their similar densities and altitudes. Figure 7 compares the temperatures and ATs of the two stations. The differences between the temperatures measured at Stations 4 and 5 were not significant during the period from 00:00 to 6:00 in the autumn, ranging from 0.02 °C to 0.9 °C. The original temperatures measured at the two stations were highest during the period from 12:00 to 18:00 in the summer: 31.85 °C at Station 4 and 31.91 °C at Station 5, which presented a difference of 0.06 °C. The differences between the ATs and the original temperatures were greatest during the period from 18:00 to 24:00 in the summer: 2.41 °C at Station 4 and 4.45 °C at Station 5. The highest AT of Station 4 was 34.5 °C, and that of Station 5 was 36.17 °C, the two differing by 1.67 °C. At Station 5, where the wind speeds were lower, the difference between the original temperature and the calculated AT was 4.45 °C, whereas at Station 4, where the wind speeds were higher, the difference between the original temperature and the calculated AT was 2.65 °C. The temperatures measured at the two stations did not differ significantly, but the inclusion of wind speed in the AT calculations resulted in greater differences, as greater wind speeds can indeed carry away more heat.

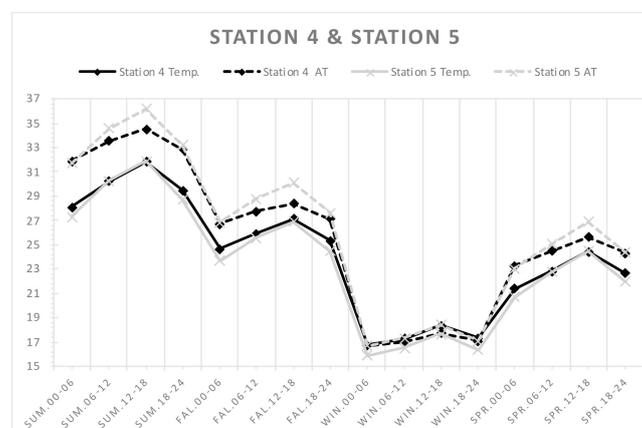


Figure 7. Comparison of temperatures and ATs at Stations 4 and 5.

- Discussion on enthalpy

The SEM analysis results indicate that aside from wind speed and temperature exerting a significant impact on the thermal environment, humidity is another crucial weather factor needed to understand the features of hot and humid climates. The thermodynamic factor that coexists with humidity is enthalpy, which is the total heat held by the air. We therefore used enthalpy to discuss the influence of humidity on the thermal environment.

Figure 8 compares the temperatures and enthalpy values of the weather stations discussed above. As can be seen, Station 1 is located in an area with lower building density, and lower temperatures were measured there. However, its enthalpy values were higher than those of some of the other weather stations with higher temperatures. Looking at the humidity levels in Figure 9, we can see that the average humidity measured at Station 1 was 89.8%, which was higher than averages of the remaining weather stations by 10–15% except for that of Station 2, which was 92.2%. We found that in areas where the measured temperatures do not indicate high thermal energy, those with high enthalpy values also had relatively higher humidity. The enthalpy values of Station 1 presented high thermal energy, and despite lower temperatures, highly humid areas turn moisture into moist enthalpy, which increases thermal energy. As a result, the enthalpy values at Station 1 were higher than those at the other stations during the period from 12:00 to 18:00 in the summer. The comparison in Figure 10 shows that the average wind speed measured at Station 1 was 0.02 m/s, which was fairly low. In our discussion in the previous section, we mention that strong winds can carry away more heat, and therefore, at Station 1, where the humidity was high and wind speeds were low, the enthalpy values indicated high thermal energy. Enthalpy is the thermal energy held by both dry and moist air and more adequately explains the distributions of thermal energy in urban microclimates.

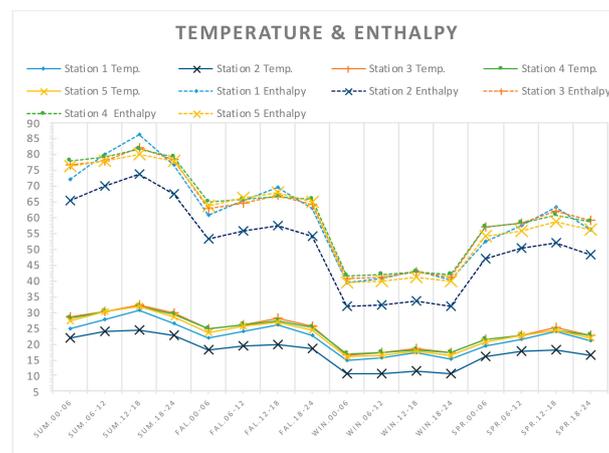


Figure 8. Comparison of temperatures and enthalpy measured at weather stations.

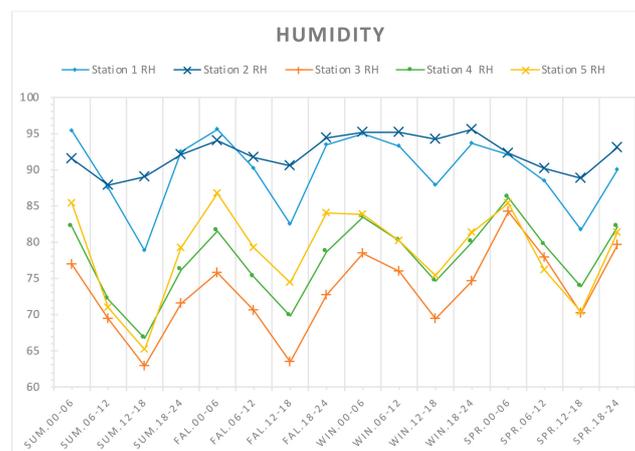


Figure 9. Comparison of humidity measured at weather stations.

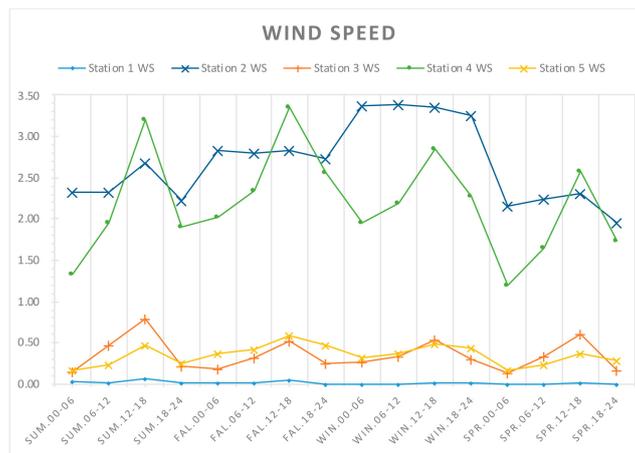


Figure 10. Comparison of wind speeds measured at weather stations.

Similar to Station 1, Station 2 was also located in a more humid area. However, its enthalpy values were the lowest. Its average wind speed was also the highest (2.67 m/s).

3.3.3. Analysis of AT Range for Thermal Comfort

The comfort analysis below was conducted using AT. The ATs of the weather stations were higher than the original temperatures by 0.2–4.8 °C in summer. Except for those of Station 2, the ATs were lower than the original temperatures in winter. Table 1 presents the AT range for thermal comfort as provided by the Central Weather Bureau, which is between 21 °C and 32 °C and close to the PET range for thermal comfort, namely, between 22 °C and 34 °C, established by T.-P. Lin and Matzarakis [44]. We can therefore look at the thermal comfort zone using Figure 11.

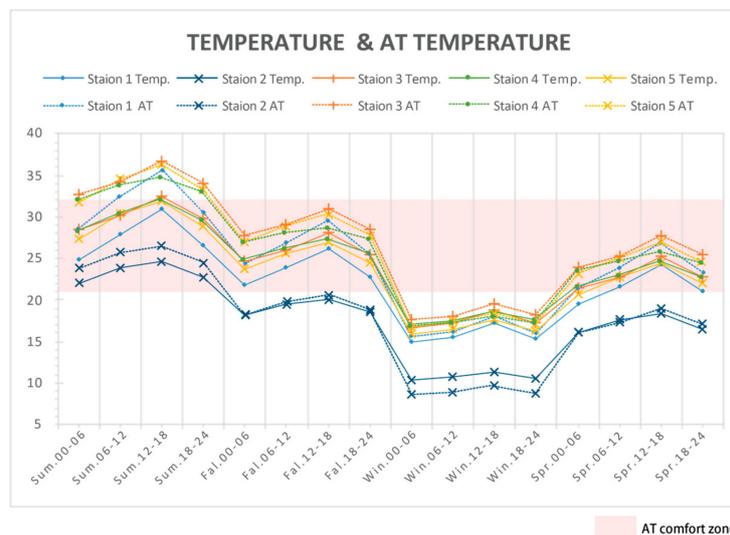


Figure 11. AT comfort zone.

In summer, the ATs of Station 2 at all times of the day and those of Station 1 from 00:00 to 06:00 and from 18:00 to 24:00 fell within the comfort zone, whereas the remainder fell outside the comfort zone. In contrast, the ATs of Station 2 in spring and autumn fell outside the comfort zone, while those of the other weather stations fell inside the comfort zone. Station 2 is located where the building density is low and the altitude is high. As established in this study, location and building density influence the thermal environment. We also discovered that in addition to causing uncomfortably hot temperatures, location and building density can also cause uncomfortably cold temperatures. In winter, the ATs of all five weather stations fell outside the comfort zone.

The AT indicates that the temperature and humidity of the air in the environment exert a significant and combined effect on the human body. The AT is therefore a suitable means of reflecting human perception of temperature. The data revealed that ATs could easily exceed 32 °C in summer, but when cold continental air masses hit in winter, northeast winds increase the chance of ATs under 10 °C.

3.3.4. Comfort Zone on Psychrometric Chart

This section uses a psychrometric chart to discuss the variable factors of thermal comfort. We plotted the comfort zone and the measurements collected by the weather stations on a psychrometric chart (see Figure 12). As can be seen, most of the measurements fell outside the comfort zone.

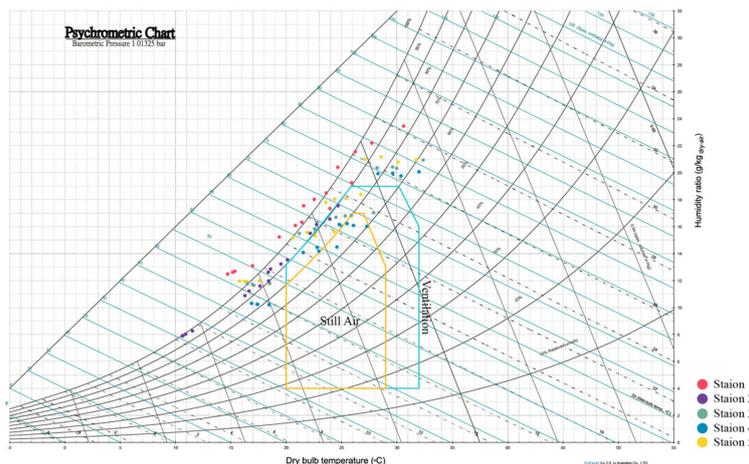


Figure 12. Psychrometric chart of comfort zone and weather measurements.

All five stations measured conditions that fell outside the comfort zone in summer. The data points fell in regions with temperatures between 28 °C and 33 °C and humidity over 60%. Due to high humidity (80–95%) and low wind speeds, the enthalpy surrounding Station 1 could not easily dissipate, so its data points fell in high humidity regions in the psychrometric chart. Dehumidification alone would put them in the comfort zone. Station 5 measured similar conditions to Station 1 but with 65–85% humidity. In spring and autumn, the weather was windy around Station 3, and its data points fell within the comfort zone. Although Station 3 measured lower wind speeds and similar temperatures to those of other stations, it measured lower humidity and was therefore most comfortable in spring and autumn. The temperatures at Station 3 in summer would require cooling and dehumidifying to fall within the comfort zone. Station 4 measured temperatures and humidity similar to those of Station 3. The data points of Station 4 fell within the comfort zone from 00:00 to 05:00 in summer, from 06:00 to 23:00 in autumn, and from 12:00 to 17:00 in spring. The higher wind speeds at Station 4 increased comfort levels. Station 2 was humid all year round, with average humidity of 92%. Due to low building density, high altitude, and high average wind speed, the temperatures measured by Station 2 were low, but dehumidification could put its data points in the comfort zone.

The psychrometric chart shows that ventilation can improve thermal comfort. In ventilated conditions, the comfort zone is larger. Wind can carry away humidity and thermal energy. In conditions where thermal energy accumulates, reducing enthalpy requires sensible cooling only, cooling and dehumidifying, or dehumidifying only to move data points to the comfort zone. In the psychrometric chart, lowering the dry- and wet-bulb temperatures can shift data points into the comfort zone. Our results indicate that urban heat island effects prevent heat dissipation in urban environments, which makes it uncomfortably hot for the human body. Our results also indicate that low temperatures make it uncomfortably cold.

3.4. General Discussion

This study examined various urban forms and weather factors to identify the factors with the greatest impact on the thermal environment, investigate the relationship between weather factors and thermal comfort, and understand whether urban form influences the heat experienced in urban environments.

High temperatures cause environmental issues and severe human health problems. Although the human body can maintain a core temperature of around 37 °C, a number of factors such as high temperatures and humidity, clothes, physical exercise, and dehydration affect the balance of heat in the human body [52]. Standards of indoor and outdoor thermal comfort may also vary with culture, climate, season, acclimatization, expectation, experience, and region [53,54]. The PET range for thermal comfort in Central and Western Europe is 18–23 °C [26]. To investigate the influence of heat acclimatization on the seasonality of thermal comfort, a research team in Taiwan proposed that the temperature range for thermal comfort is 26–31 °C in the summer and 23.7–29.7 °C in the winter [35]. Research has shown that differences in thermal comfort exist between dry climate and the hot and humid climate of Taiwan.

Researchers have indicated that research on thermal comfort cannot merely discuss temperature [30]. Thermal comfort requires an analysis of the relationships between relevant factors and the climate zone, such as air temperature, relative humidity, wind speed, and solar radiation. These outdoor thermal environment factors all influence the assessment of thermal comfort [23,25]. Relevant studies have revealed that higher wind speeds result in greater outdoor temperature differences [52], and after real-world measurements were input into simulation software, it was found that wind can help lower air temperature and increase comfort [23]. Emmanuel [55] found evidence that increasing wind speeds can mitigate urban heat island effects, enhance outdoor thermal comfort, and also disperse air pollutants. This has been confirmed by further studies, which showed that wind can greatly reduce urban heat island effects [52,56,57], prevent local heat accumulation [58], and increase the thermal comfort of the urban environment [59]. The air temperature can rise with no significant changes in thermal comfort. This is because the thermal comfort of the human body is determined not only by temperature but also by relative humidity [60].

Urban forms also influence the microclimate [19,61]. Terrain has a clear impact on urban heat islands [30]. Essentially speaking, urban climate, road axes, and building height are directly associated with Urban Heat Island attributes [57], and building height influences urban density, which in turn influences urban climate [62]. Relevant research has shown that urban thermal conditions are influenced by urban development factors [63]. Thus, location, building density, and urban form have varying degrees of influence on the thermal environment, which in turn impacts thermal comfort. The outdoor environment can affect the quality of indoor comfort. Factors such as temperature, humidity, wind direction, wind speed, and enthalpy in the urban environment also directly affect the indoor environment.

Givoni [64] divided the environmental indices that influence thermal comfort into temperature, humidity, and wind speed, which are identical to the humidity and wind speed results of our SEM analysis. The results of this study indicate that thermal comfort varies even more significantly with changes in humidity and wind speed. In the hotter seasons (summer and autumn), thermal comfort is higher than the original temperature, whereas in the colder seasons (winter and spring), it is lower than the original temperature, which may be the result of wind speed [65].

Based on the analysis above, we used an AT formula that takes the combined effects of temperature, humidity, and wind speed into account, and it can be used for flat or mountainous regions or for hot or cold seasons. Our AT results were higher in hot seasons and lower in cold seasons, which reflects human perceptions of temperature and ensures good applicability. The high wind speeds in the subtropics in winter may bring discomfort to people outdoors [57]. Among the environmental indices, both humidity and wind speed have a significant impact on thermal comfort, but in the subtropics, humidity has the greater influence. Humidity had a greater weight in our AT formula, so it

is more suitable for the subtropics. The urbanization in Taiwan is quite high. The results of this study can be applied basically for the six major cities in Taiwan, yet they should be modified by different model of factors. For example, Taoyuan and Taichung are on the tableland, and height factor has been considered in the original model, so in those two cities it should be directly applicable. However, Tainan and Kaohsiung need to be corrected for sea-land breeze impact factors. As for the countryside, small towns they are less applicable. The results of the research model show that the urban thermal environment is mainly affected by humidity and wind speed in different terrains.

4. Conclusions

Unlike the previous urban heat islands research by measurement, modeling/simulation, and telemetry, this study discusses the relationship between meteorology and thermal comfort through structural equation modeling. Urban forms exert influence on the thermal environment in the subtropics mainly because the location of the urban environment, the distributions and densities of buildings in the region, and the humidity and wind speed in the urban climate environment have significant influence on enthalpy and AT. This suggests a strong connection between urban thermal environments and weather patterns.

Humidity is closely associated with comfort, and the high humidity in the subtropical climate of Taiwan means people often perceive the weather as uncomfortable. The influence of latent heat and enthalpy on comfort must be considered, and enthalpy is also heavily influenced by wind. Wind is a weather factor that can be used to improve the thermal environment. In urban planning, building volume should be coordinated to form a wind corridor to take heat away from the area. The quantitative statistics in this study show that the urban thermal environment is influenced by urban forms. To mitigate urban heat island effects, a comprehensive discussion of various environmental factors is needed. Urban climate research is necessary so that urban planning can improve the comfort of urban residents and effective and comprehensive measures can be designed to relieve urban heat island effects.

Author Contributions: C.-H.H.: Conceptualization: Ideas; formulation or evolution of overarching research goals and aims. H.-H.T.: Writing - review & editing: Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages. H.-c.C.: Investigation: Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection. All authors have read and agreed to the published version of the manuscript.

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