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An Approach for Quantifying a Regional Haze Stress: Case Study in Three Cities of Taiwan

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Abstract: This study proposes an approach of evaluating the haze stress index (HSI) and quantifying people's feelings for haze stress. The three special municipalities in Taiwan were selected as representative cities of slightly, moderately, and heavily contaminated with fine particulate matter ($PM_{2.5}$) to evaluate the adaptability of the proposed approach. Equations with weightings of parameters to evaluate four temporal HSIs—hourly, daily, monthly, and yearly HSIs—were established. The parameters were measured $PM_{2.5}$, relative humidity, and secondary organic aerosol (represented by the sum of measured O_3 and NO_2). The results of evaluating the HSIs in the three cities demonstrated that the inverse-variance weighting method is the best because the haze stress sensitivities in the four temporal periods were higher than those obtained using the unit and variance weighting methods to respond to the real situation of air quality. Variation in the four temporal HSIs for the three cities demonstrates that the variation increases with an increasing level of air pollution. When comparing between 2015 and 2018, the fractional reductions in HSIs in the slightly, moderately, and heavily contaminated cities were ≤18.4%, ≤10.8%, and ≤11.3%, respectively. It is recommended that the HSIs are categorized into five haze stress groups based on the haze stress level. The people's feelings in the three cities on the haze stresses were represented using the established quantifying descriptors in detail. The results show that the proposed approach can provide quantification indices of haze stress and people's feelings in a regional haze, thereby firmly establishing the governmental improvement policy.

Keywords: ambient haze; quantification index; secondary organic aerosol; fine particulate matter

1. Introduction

A number of environmental indices are used to state regional air quality. The air quality index (AQI) was developed by government agencies to communicate the degree to which air pollutants affect human health at a given time. The AQI is based on the maximum values of the subindices of pollutants—fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3). The air quality health index is a multipollutant index model that is based on the observed relationship between the 3-h average concentrations of O_3, NO_2, and $PM_{2.5}$ that are harmful to health [1,2]. Plaia et al. [3] proposed a multipollutant–multisite air quality index approach for considering the combined effect of various pollutants in the environmental quality over time. Thach et al. [4] aggregated the subindices of PM_{10}, SO_2, NO_2, and O_3 by using the root-mean-power function to construct an overall AQI on health. Gorai et al. [5] proposed the fuzzy air quality health index to deduce the health risk associated with local air pollution levels. Stergiopoulou et al. [6] used two ozone AQIs to evaluate the association between daily ozone concentration and the daily occurrence of respiratory symptoms and peak expiratory flow. Huang et al. [7] proposed a land contribution index to quantify the seasonal contribution of coupling urban land use types on an urban heat island. Bagieński [8] developed the traffic air quality indices (TAQIs) for evaluating air quality near roadways and defining the degree of harmfulness. Baumüller and Reuter [9] introduced the ratio of the area represented by a monitoring station to the total urban area as a weight into an AQI to form an urban area pollution index.

People recognize air pollution when it causes haze or poor visibility. Haze affects people's sentiments and emotions [10,11]. Many researchers have examined the health effects of haze [12]. Yaacob et al. [13] examined whether haze reduces peak expiratory flow rate (PEFR) or negatively affects respiratory function. The results revealed a significant reduction of more than 15% in the expected PEFR. However, the rate of respiratory illness in children was higher than the expected value. Ramakreshnan et al. [14] systematically reviewed the physical and psychological health effects of haze according to the available literature pertaining to Association of Southeast Asian Nations countries. Moreover, consistent evidence has been found for an increase in respiratory morbidity due to haze. However, there is no evidence for cardiovascular morbidity and cancer risk due to haze. A higher number of studies on potential haze-induced morbidity and more efficient public health planning in terms of haze-induced morbidity are required for developing countries. Regional haze reduces irradiance in agricultural areas, which decreases crop yields [15]. Moreover, haze causes economic [16], social and low productivity [17], high traffic [18], and high suicide mortality [19] problems.

The idea of air stress indices (ASIs) was first proposed by Baumüller and Reuter in 1995 [9]. The planning-related ASI has two structures: ASI_1 for annual average air pollution stress and ASI_2 for short-term air pollution stress [20,21], which are the sums of the mean reference value ratio of SO_2, NO_2, PM_{10}, and benzene and for SO_2, NO_2, PM_{10}, and CO, respectively. The daily air quality index (DAQI) and daily air stress index (ASI_{BW}) were developed by Mayer et al. [21] and the Federal State Institute for Environmental Protection Baden-Wuerttemberg, Germany [22] and they consider five criteria pollutants (SO_2, NO_2, O_3, CO, and PM_{10}). In the DAQI and ASI_{BW} calculations, a pollutant's highest daily 1-h or 8-h mean value is used, and reference values temporally correspond to European Union standards. Kassomenos et al. [23] used ASI_{BW} to assess heavily polluted urban areas (Thessaloniki City, Greece), and the assessment results were compared with the results obtained using the AQI [24] and DAQI index. The three methodologies provided approximately consistent results that the air quality is bad and unhealthy in the urban area.

None of these above indexes reflect people's concerns on the deterioration of ambient haze. To quantify the degree of haze stress, this study proposes an approach to evaluate the haze stress index (HSI) in a region. The three cities—slightly, moderately, and heavily contaminated with $PM_{2.5}$—were selected as representative regions to evaluate the adaptability of the proposed approach. Equations to evaluate four temporal HSIs—hourly, daily, monthly, and yearly HSIs—were established. The equations use an optimum weighting method to obtain the normalized weights of the following three selected air pollutant and meteorological parameters—measured $PM_{2.5}$, relative humidity (RH), and secondary organic aerosol (represented by the sum of the measured O_3 and NO_2). The comparison of fractional reduction in the hourly, daily, and monthly HSIs of the three cities between 2015 and 2018 was conducted. A categorical method for determining haze stress was recommended in this study. The people's feelings in the three cities on the haze stress were represented using the established quantifying descriptors of haze stress.

2. Materials and Methodology

2.1. Target Cities and Selected Representative Air Quality Monitoring Stations

Taiwan is an island with an area of 35,883 km^2 and mostly comprises rugged mountains that include five high ranges with an altitude higher than 3000 m from the northern to the southern tip of the island and the flat to gently rolling plains in the west (Figure 1). Taiwan has a high-income advanced economy and a highly urbanized island, with more than 70% of its residents living in the urbanized area. The estimated population in 2018 was 23.58 million. New Taipei City, Taichung City, and Kaohsiung City, which are three special municipalities in Taiwan, were selected as target cities in which to evaluate the adaptability of this approach. New Taipei City, Taichung City, and Kaohsiung City are located in northern, central, and southern Taiwan, respectively. New Taipei City has the highest population of any city in Taiwan, with 3.99 million residents; followed by Taichung City, with 2.81 million; and Kaohsiung City, with 2.77 million (2018). In terms of geographic location, New Taipei City and Taichung City are located in basins (the Taipei Basin and Taichung Basin). Kaohsiung City is located on a large plain (the Kaohsiung Plain) (Figure 1). In this study, for each city, a representative air quality monitoring station (AQMS) was selected, from which to draw air quality data for the calculation of haze stress in Xinghuang, Xitun, and Siaogang in New Taipei City, Taichung City, and Kaohsiung City, respectively (Figure 1). These representative AQMSs were selected because they are located in the densely populated downtown of each city.

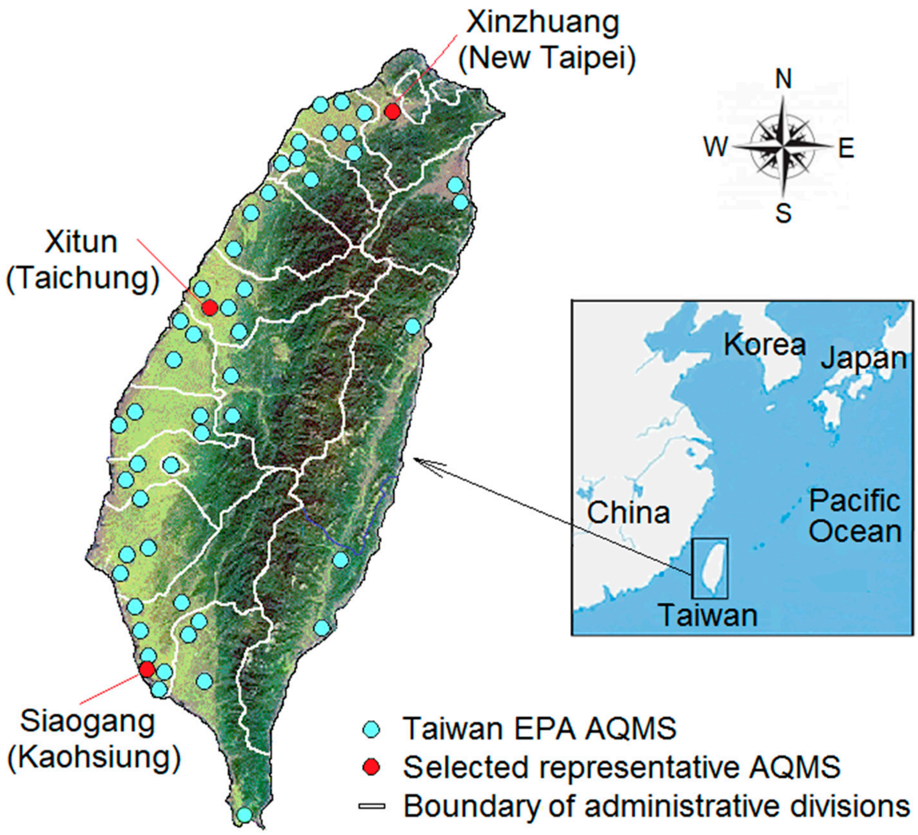

Figure 1. Locations of three municipalities and their selected representative AQMS.

Monitoring data (https://taqm.epa.gov.tw/taqm/tw/default.aspx) of air pollutants and meteorology from the three selected representative AQMSs were used to calculate the hourly, daily, monthly, and yearly HSIs in the three target cities. In Taiwan, AQI has been adopted since 1 December 2016 as the basis for determining air quality standards. Table 1 lists the pollutant concentration breakpoints and AQI index of Taiwan, which is similar to that of U.S. and most Asian countries. In this study, some AQI standards of $PM_{2.5}$, O_3, and NO_2 will be used to establish regional HSIs as the recommended reference limits.

Table 1. Pollutant concentration breakpoints and AQI index of Taiwan.

AQI Category (Range)	Particulate Matters (μg m^{-3})		O_3 (ppb)		NO_2 (ppb) [1 h]	CO (ppm) [8 h]	SO_2 (ppb) [24 h]
	PM_{10} [24 h]	$PM_{2.5}$ [24 h]	[8 h] (2)	[1 h] (1)			
Good (0–50)	0–54	0.0–15.4	0–54	–	0–53	0–4.4	0–35
Moderate (51–100)	55–125	15.5–35.4	55–70	–	54–100	4.5–9.4	36–75
Unhealthy for sensitive groups (101–150)	126–254	35.5–54.4	71–85	125–164	101–360	9.5–12.4	76–185
Unhealthy (151–200)	255–354	54.5–150.4	86–105	165–204	361–649	12.5–15.4	186–304
Very unhealthy (201–300)	355–424	150.5–250.4	106–200	205–404	650–1249	15.5–30.4	305–604
Hazardous (301–500)	425–504	250.5–500.4	–	405–604	1250–2049	30.5–50.4	605–1004

(1) Areas are generally required to report the AQI based on 8-h ozone values. However, there are a small number of areas where an AQI based on 1-h ozone values would be more precautionary. (2) 8-h O_3 values do not define higher AQI values (≥301). AQI values of 301 or higher are calculated with 1-h O_3 concentrations.

2.2. Weighting Methods

The following four methods were used to obtain the weight: unit, statistical, variance, and inverse-variance weighting methods.

(1) Unit weighting: In this method, the weights between n indicators are not considered. Each indicator has equal importance in the evaluation. The formula of unit weighting is as follows:

$$w_1 = w_2 = \ldots = w_n = 1 \tag{1}$$

(2) Statistical weighting: In this method, the weights are set inversely proportional to the score. The purpose of this method is to retain information on low-level indicators. The formula of statistical weighting is as follows:

$$w_i = \frac{1}{c_i}, \quad i = 1,\ 2,\ \ldots, n \tag{2}$$

where c_i is the concentration of indicator i.

(3) Variance weighting: This method is used when the variation in data is inconsistent to reduce the data importance of larger variation indicators. Therefore, indicators with a smaller variation in data have greater weight. The formula of variance weighting is as follows:

$$w_i = \frac{1}{\sigma_i^2}, \quad i = 1,\ 2,\ \ldots, n \tag{3}$$

where $1/\sigma_i{}^2$ is the variance, which can be calculated using the following equation:

$$\sigma^2 = \frac{1}{N}\sum_{j=1}^{N}(c_j - \mu)^2 \tag{4}$$

where N and μ are the number of terms in the distribution and the mean of data, respectively.

(4) Inverse-variance weighting: This method is exactly opposite to the variance weighting method, which reduces the data importance of lower variation indicators. The formula of inverse-variance weighting is as follows:

$$w_i = \sigma_i^2, \quad i = 1,\ 2,\ \ldots, n \tag{5}$$

Each indicator in the regional HSI is a sufficiency condition rather than a necessity condition. Moreover, variance is used to quantify the variation in a set of data, which is applicable when apparent variations appear during air pollutant monitoring. In this study, the unit, variance, and inverse-variance weighting methods were investigated and compared to obtain an optimal weighting method. Moreover, the weights were normalized to make the established regional HSI equations more regular. The formula of the normalized weight W_i of indicator i is as follows:

$$W_i = \frac{w_i}{\sum_{j=1}^{n} w_j} \quad (6)$$

where the denominator is the sum of the original weights.

3. Results and Discussion

3.1. Establishing Regional HSIs

Many countries in Asia have experienced severe haze pollution [5,25,26]. Some previous studies used various analytic methods and tools, such as the inductively coupled plasma mass or atomic emission spectrometer for heavy metals, ion chromatography for water-soluble ions, the thermal or optical carbon analyzer for organic and elemental carbons, and the microvolume spectrophotometer for microbial deoxyribonucleic acid in haze, to determine the chemical and microbial components of haze [26–29]. These fine analytical results cannot be used as parameters to establish HSIs because they are not items monitored by AQMSs. Haze, like smog, has tiny suspended solid or liquid particles [30] that reduce horizontal visibility to less than 10 km [31]. Hunova [32] presented a visualization method for measured air quality data that uses ambient air pollution (the rank average of annual median 24-h average concentrations of SO_2, NO_x, CO, PM_{10}, Cd, and Pb), ground-level ozone, and wet atmospheric deposition as factors. Kim et al. [33] indicated that the oxygenated organic component in interstitial aerosol is similar to that in fog water ($r^2 > 0.95$), which is attributable to the moderately oxidized low-volatility dissolved organic matter under humid conditions. Some previous studies have investigated the formation of a secondary organic aerosol (SOA) from various organic compounds [33–35] and determined that the level of SOA is usually underestimated [36]. Ren et al. [37] indicated that high-molecular-weight n-alkanes and fatty acids dominated the particles with an aerodynamic diameter greater than 1.1 μm in terms of their concentration during severe haze days. Ultrafine particles (aerodynamic diameter: 0.001–0.1 μm) are typically present in a high concentration in an urban environment [38]. SOA is an important component of ultrafine aerosols in the ambient atmosphere and is a gas phase product of atmospheric oxidation and condensation of volatile organic compounds [39]. Photochemical reactions are the main formation pathways of SOAs [40], and the concept of odd oxygen ($O_x = O_3 + NO_2$) is often used to study the photochemical formation of SOAs [41–43]. Zhu et al. [44] indicated that SOA was the largest contributor to the scattering coefficient of PM_1 during haze episodes, accounting for 45.5%. In our previous study, a method was established to quantify accurately the source apportionment of ambient haze from measured $PM_{2.5}$, moisture, and SOA [45]. In Taiwan, the height of sampling ports of most AQMSs is 3–15 m from the ground. Therefore, the measured data of $PM_{2.5}$ does not represent all the haze in the sky. In addition, high air moisture can affect people's feelings, causing them to feel particularly uneasy and discomfort [46]. The strongly enhanced aerosol extinction coefficient is due to hygroscopic growth at high moisture conditions [47]. Liu et al. [48] indicated that RH was related to the high particle concentrations in haze episodes. Moisture is often mixed in haze, so moisture must also be considered for haze stress.

Sulfate, nitrate, and ammonium are the dominant species in secondary inorganic aerosol (SIA) [49,50]. Some gaseous species (such as NO_2, SO_2, and NH_3) can be adsorbed on to the existing particles and then undergo chemical transformation to produce SIA [51] or acid rain [52]. The formation of SIA plays a key role in the increasing $PM_{2.5}$ concentration [53], especially on the days with high relative humidity [54]. Therefore, SIA (the sum of NH_4^+, NO_3^-, and SO_4^{2-}) mainly exists on $PM_{2.5}$ [50]. In addition, general air quality monitoring stations do not monitor the SIA concentration so that no SIA data can be used directly. Thus, SIA is not considered separately in the evaluation of ambient HSI. Some meteorological parameters, such as wind speed, temperature, solar irradiance, and pressure, can affect the formation of haze, but this study does not discuss the cause of formation of haze. Therefore, the real existing haze was estimated by three main components ($PM_{2.5}$, moisture, and SOA) that can be measured by AQMS. The concentrations of fine particles ($PM_{2.5}$), RH (represented moisture), and SOA (represented by $[O_3 + NO_2]$) were used to establish the relationship between equations of the HSI during various periods:

(1) Hourly HSI (HSI_{hourly}):

$$HSI_{hourly} = W_{PM_{2.5}} \frac{[PM_{2.5}]}{35.5\ \mu g\ m^{-3}} + W_{RH} \frac{RH}{70\%} + W_{O_x} \frac{[O_3]+[NO_2]}{170\ ppb} \quad (7)$$

(2) Daily HSI (HSI_{daily}):

$$HSI_{daily} = W_{PM_{2.5}} \frac{[PM_{2.5}]}{25\ \mu g\ m^{-3}} + W_{RH} \frac{RH}{70\%} + W_{O_x} \frac{[O_3]+[NO_2]}{139\ ppb} \quad (8)$$

(3) Monthly HSI ($HSI_{monthly}$):

$$HSI_{monthly} = W_{PM_{2.5}} \frac{[PM_{2.5}]}{15\ \mu g\ m^{-3}} + W_{RH} \frac{RH}{60\%} + W_{O_x} \frac{[O_3]+[NO_2]}{107\ ppb} \quad (9)$$

(4) Yearly HSI (HSI_{yearly}):

$$HSI_{yearly} = W_{PM_{2.5}} \frac{[PM_{2.5}]}{15\ \mu g\ m^{-3}} + W_{RH} \frac{RH}{60\%} + W_{O_x} \frac{[O_3]+[NO_2]}{80\ ppb} \quad (10)$$

where the denominators are the recommended reference limits of the selected air pollutants or meteorological parameters for hourly, daily, monthly, or yearly HSIs. These limits are based on the AQI and health implications in Table 1 and suitable conditions with respect to the weather in Taiwan. For $PM_{2.5}$ and odd oxygen ($[O_3 + NO_2]$), the recommended limits of hourly, daily, monthly, and yearly periods are the concentrations corresponding to their AQI of 100, 75, 50, and 50 (Table 1), respectively. These recommended limits are based on the hourly, daily, and monthly/yearly AQIs, which can be "good", "between good and moderate", and "moderate", respectively. In Taiwan, the annual average concentration standard of each criteria pollutant is its concentration corresponding to AQI of 50. Therefore, the concentration corresponding to AQI of 50 was recommended as the limits of monthly and yearly periods. People tend to feel most comfortable at an RH range of 30–50%, and the range of about 30–70% is healthy for humans [55]. The higher the RH, the less the sweat evaporates, which seriously affect the body's thermoregulation [56] and people's emotions. People feel stuffy and uncomfortable when RH is about 80%, and it is very sticky when RH is higher than 90%. The range of monthly average RH in Taiwan was 73–81%, and those for which the maximum and minimum are in February and in July, respectively. This RH range occurs widely in some major cities, such as Los Angeles, Chicago, Singapore, Bangkok, and Shanghai [57–59]. According to the factors mentioned above, the recommended RH limits of hourly, daily, monthly, and yearly periods are RHs of 70%, 70%, 60%, and 60%, respectively. However, the selection of suitable denominator values is important for an administrator, which can be changed according to the regional environmental characteristics.

3.2. Spatial and Temporal Variations in $PM_{2.5}$, RH, and ($[O_3]$ + $[NO_2]$)

In Taiwan, the daily average limit (DAL) and annual average limit (AAL) of $PM_{2.5}$ are 35.5 and 15 $\mu g\ m^{-3}$, respectively. The southwest and northeast monsoon periods are from mid-April to mid-September and from mid-September to mid-April, respectively. Figure 2 displays the monthly average concentrations of $PM_{2.5}$ in New Taipei City, Taichung City, and Kaohsiung City during 2015–2017. The monthly average concentrations of $PM_{2.5}$ in the three cities are in the following sequence: Kaohsiung City > Taichung City > New Taipei City. This sequence reveals that the concentration of $PM_{2.5}$ increases from north to south in Taiwan. The results show that New Taipei City, Taichung City, and Kaohsiung City are slightly, moderately, and heavily contaminated with $PM_{2.5}$, respectively, especially during the northeast monsoon period. This is because Taiwan experiences the northeast monsoon for seven months, thus pollutants are transmitted mainly from the north to south. From 2015 to 2018, the monthly average concentrations of $PM_{2.5}$ in Kaohsiung City were higher than the AAL during the northeast monsoon season (November to March). In addition, Kaohsiung City is located in the south of Jianan Plain, the largest in Taiwan. Therefore, Kaohsiung's air pollutants are relatively easy to dissipate during the southwest monsoon season (April to September), with a clear annual cycle for $PM_{2.5}$ than other two cities.

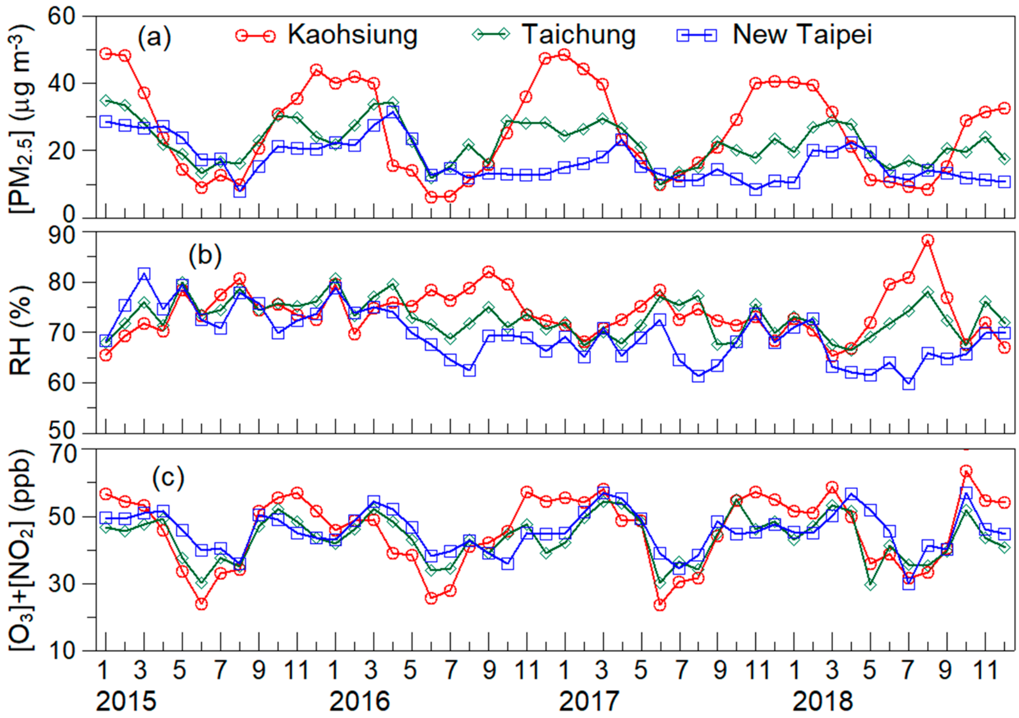

Figure 2. Monthly average concentration or percentage of (**a**) $PM_{2.5}$, (**b**) RH, and (**c**) $[O_3] + [NO_2]$ in three target cities during 2015–2018. Note that New Taipei, Taichung, and Kaohsiung are the representative cities of slight, moderate, and heavy contamination in Taiwan.

3.3. Comparison Between the Three Weighting Methods

Because the units and scales of $PM_{2.5}$, RH, and $[O_3] + [NO_2]$ are different, the statistical weighting method is not suitable for this study. As mentioned previously, the unit, variance, and inverse variance weighting methods are applicable when the variations in the data of each indicator have equal importance, thus reducing the importance of larger variation indicators and enhancing the importance of larger variation indicators. Figure 3 displays the results of computing the hourly HSI (HSI_h) in New Taipei City, Taichung City, and Kaohsiung City by using the three weighting methods during 2017. The computation results of unit weighting demonstrate that the mean values and variations in HSI_h in the three cities were all approximately constant and low throughout the day. Although the variance in HSI_h in Kaohsiung City was higher than that in the other two cities, the mean values of HSI_h were the lowest throughout the day. This is unreasonable because Kaohsiung City is heavily contaminated with $PM_{2.5}$, thus the unit weighting method is not applicable for the evaluation of haze stress.

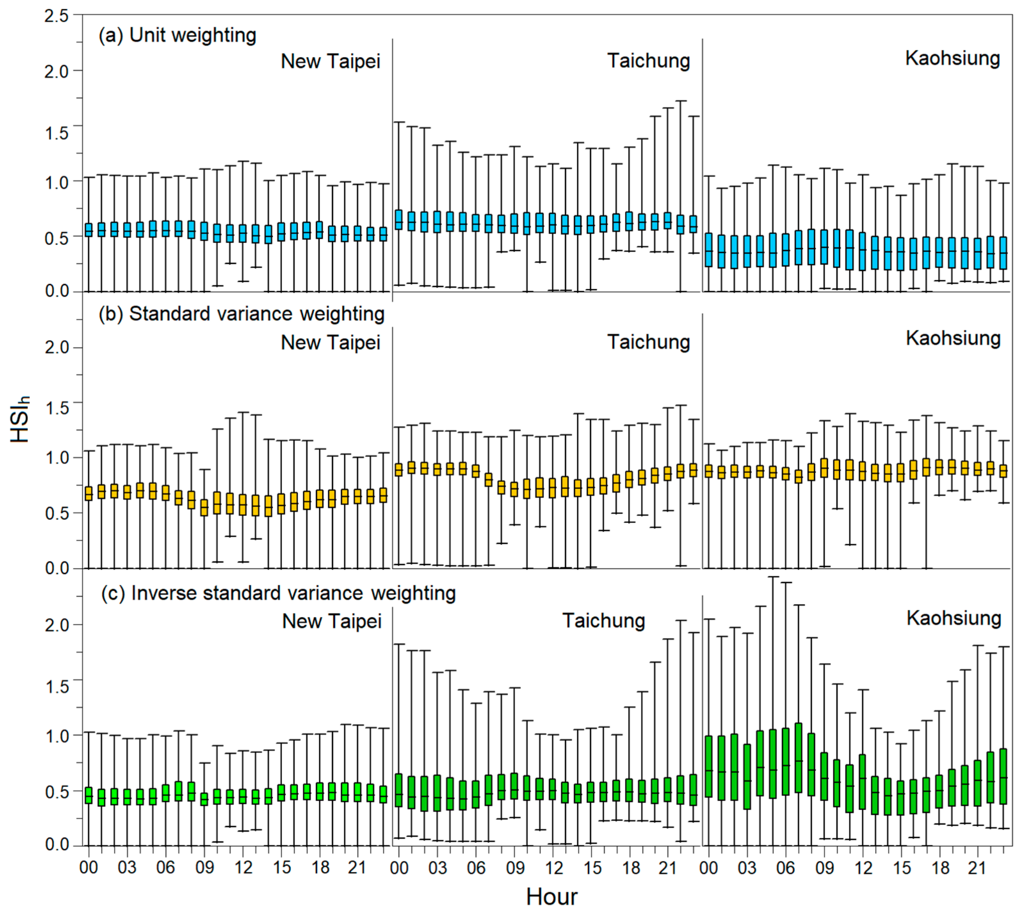

Figure 3. Box-whisker plots of the HSI_h by (**a**) unit, (**b**) variance, and (**c**) inverse variance weightings in three target cities during 2017.

The mean values of HSI_{hourly} in the three cities are in the following sequence: Kaohsiung City > Taichung City > New Taipei City, which matches the monitoring results of $PM_{2.5}$ (Figure 2). However, the variance in HSI_h for the three cities was low throughout the day (Figure 3), which is different from the fact that the concentration of pollutants in highly polluted areas varies greatly. Therefore, the variance weighting method is also not applicable for the evaluation of haze stress. The inverse variance weighting method is applicable because the mean values and variations in HSI_h in the three cities are in line with the corresponding monitoring data (Figures 2 and 3).

Moreover, because the responses of people to haze are subjective and sometimes strong, the two larger variation indicators—$PM_{2.5}$ and $[O_3] + [NO_2]$—are more important in the haze stress evaluation. Therefore, inverse variance weighting is recommended for the evaluation of the regional HSI. Here, the follow-up work uses the inverse variance weighting method.

3.4. Hourly Haze Stress

Figure 4 displays the box-whisker plots of HSI_h obtained using the inverse variance weighting method in the three cities during 2015–2018. The results demonstrate that the values of HSI_h in the three cities are consistent with their pollution situations—New Taipei City, Taichung City, and Kaohsiung City are slightly, moderately, and heavily contaminated cities, respectively. The values and variations in HSI_h in the three cities exhibited slight and small decreases by year. The HSI_h patterns of each city in different years are similar; however, the pattern differences between cities are large. Kaohsiung City has the largest value and variability of HSI_h, especially at midnight (00:00–04:00) and early morning (04:00–08:00). The means of HSI_h in New Taipei City and Taichung City are similar, but the variability of HSI_h in Taichung City is greater than that in New Taipei City. The lowest HSI_h of all three cities appeared in the afternoon (10:00–18:00). This may be due to the higher temperature during this period, which increases the mixed layer height and reduces hourly HSIs. In particular, the HSI_h pattern of Kaohsiung City exhibits a strong wave-like variation from 08:00 to 20:00, with the lowest value at approximately 14:00.

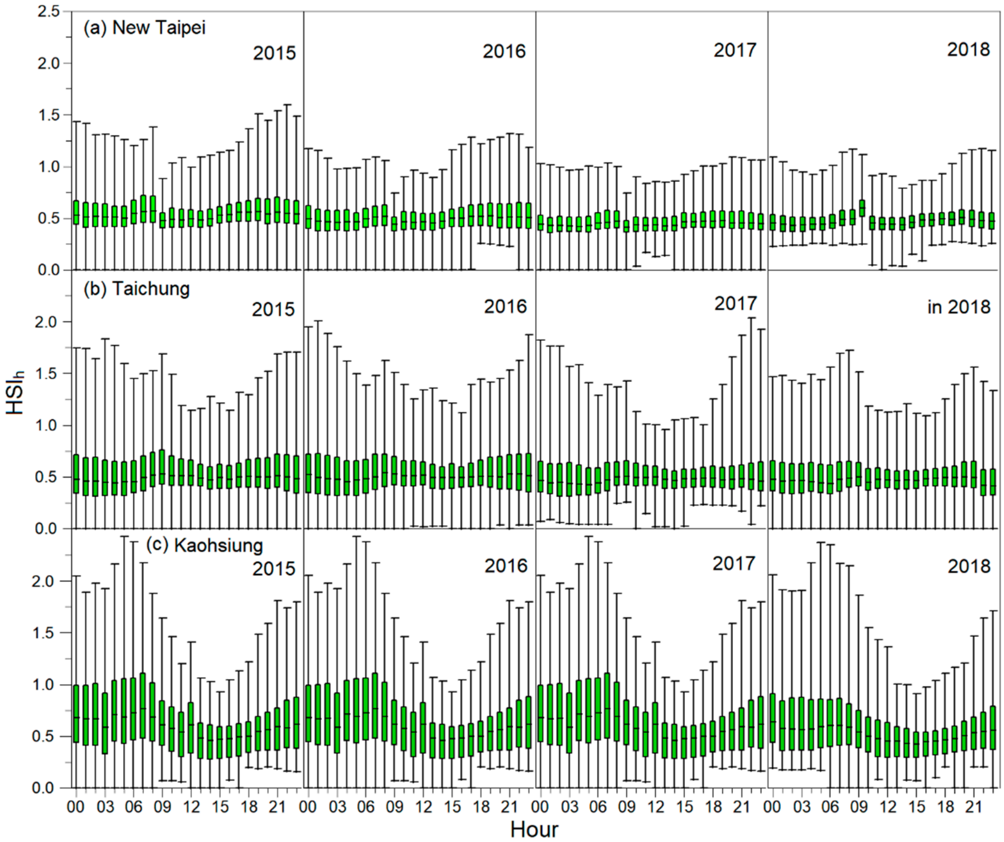

Figure 4. Box-whisker plots of the HSI_h by inverse variance weighting in the three cities during 2015–2018. (**a**) New Taipei, (**b**) Taichung, and (**c**) Kaohsiung were selected as representative cities of slightly, moderately, and heavily contaminated with $PM_{2.5}$ in Taiwan, respectively.

3.5. Daily Haze Stress

The box-whisker plots of HSI_d obtained using the inverse variance weighting method in the three cities during 2015–2018 are displayed in Figure 5. The number of days per month is different, so the amount of data calculated from 29 to 31 is also different in the calculation of HSI_d. The variations in HSI_d do not have certain criteria and are mainly affected by the daily weather. Therefore, the changes in HSI_d in the three cities are all messy. The results demonstrate that the values of HSI_d for the three cities can present their pollution statuses, which is the same as HSI_h—slight, moderate, and heavy contamination, respectively. The values and variations in HSI_{daily} in the three cities are decreasing year by year, showing an improvement in their air quality with each passing year, which is important for the government environmental protection decision makers. However, for people in the same city, there is no significant change in the daily haze stress in a month.

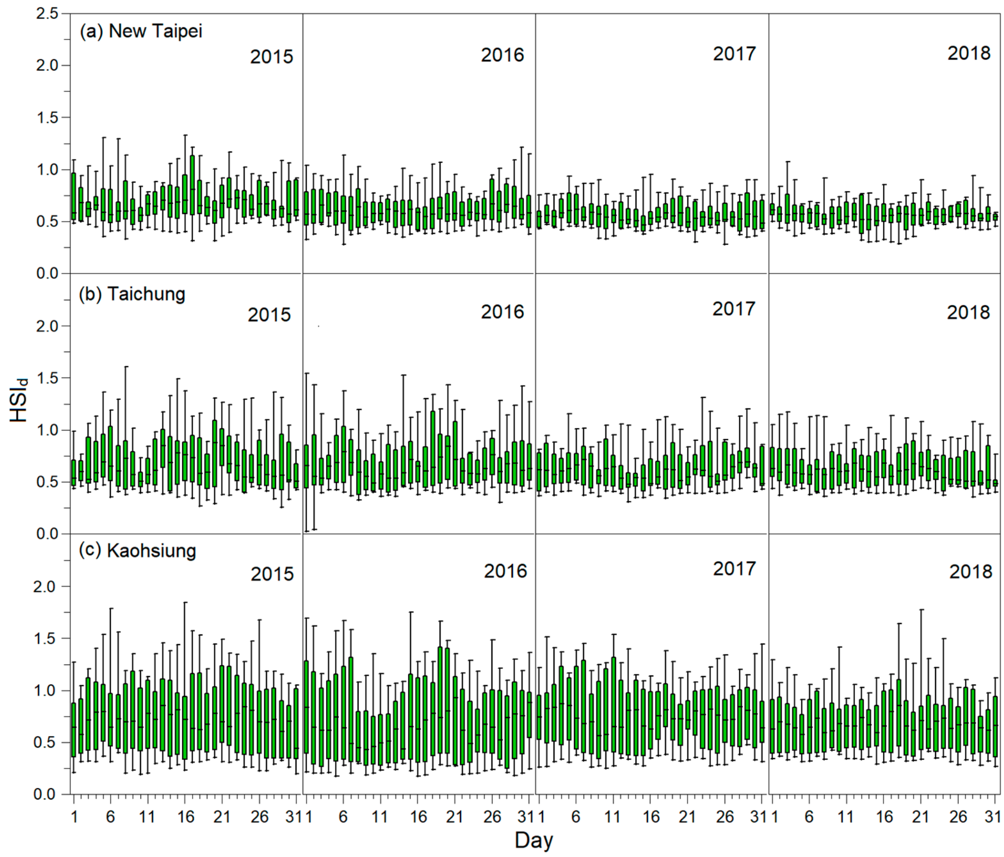

Figure 5. Box-whisker plots of the HSI_d by inverse variance weightings in the three target cities during 2015–2018. (**a**) New Taipei, (**b**) Taichung, and (**c**) Kaohsiung were selected as representative cities of slightly, moderately, and heavily contaminated with $PM_{2.5}$ in Taiwan, respectively.

3.6. Monthly Haze Stress

Figure 6 shows the box-whisker plots of HSI_m obtained using the inverse variance weighting in the three cities during 2015–2018. The HSI_m patterns of the three cities present the low- and high-polluted seasons in a year. The variation in HSI_m increases strongly by increasing the degree of air pollution in a region or city. In particular, the difference between the lowest and highest polluted month is very large in Kaohsiung City, with a maximum deviation of approximately 0.9 in the mean HSI_m. For the slightly contaminated city, New Taipei City, the difference between the low- and high-polluted months is approximately 0.3 in terms of the mean HSI_m. The lowest and highest polluted months of the three cities were June and July and January and February, which are the same as the results in Figure 2a,c, respectively. Therefore, RH is not the main cause of high haze stress. High RH occurs from June to September in Taiwan (Figure 2b). For a highly polluted region, effectively improving air quality, especially in terms of $PM_{2.5}$, can significantly reduce the HSI_m in the highly polluted months (Figure 2a).

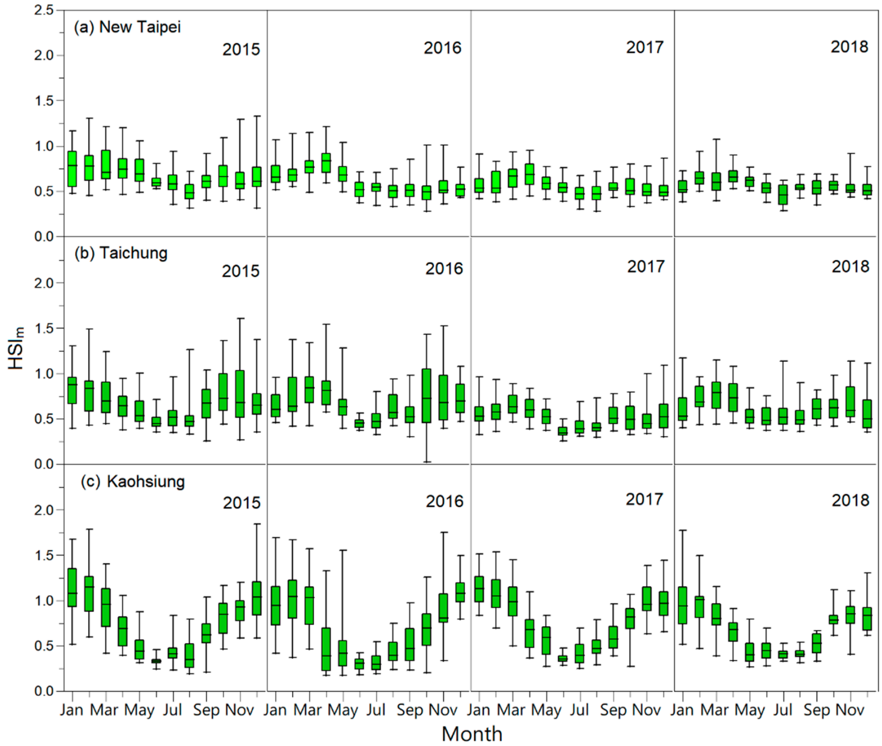

Figure 6. Box-whisker plots of the HSI_m by inverse variance weightings in the three target cities during 2015–2018. (**a**) New Taipei, (**b**) Taichung, and (**c**) Kaohsiung were selected as representative cities of slightly, moderately, and heavily contaminated with $PM_{2.5}$ in Taiwan, respectively.

3.7. Yearly Haze Stress

The bar charts of HSI_y obtained using the inverse variance weighting method in the three cities during 2015–2018 are displayed in Figure 7. In the yearly haze stress evaluation, the regional variation significantly increases with the degree of contamination. The results indicate that the change in HSI_y of Kaohsiung City is up and down, which is different from the trends of HSI_h, HSI_d, and HSI_m in the years (Figures 3c, 4c and 5c). The change in HSI_y of Taichung City is small. By contrast, the change in HSI_y of New Taipei City exhibits a significant decrease each year. The HSI_y values of the three cities were all greater than 1.0, which indicate that improvements of the air quality are still needed.

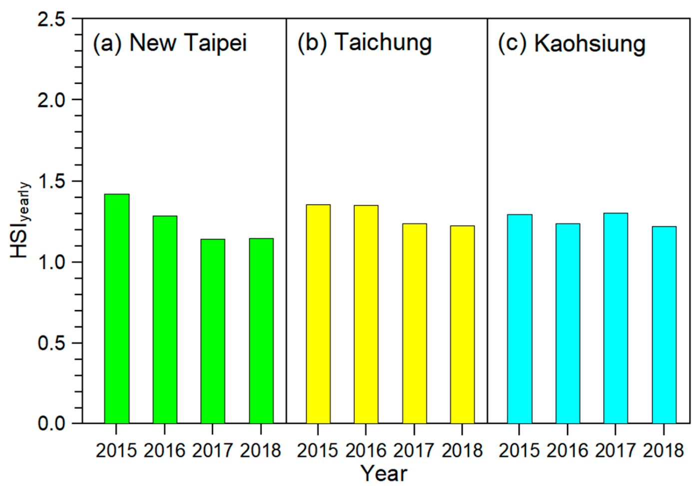

Figure 7. Bar charts of the HSI_y by inverse variance weighting in the three target cities during 2015–2018. (**a**) New Taipei, (**b**) Taichung, and (**c**) Kaohsiung were selected as representative cities of slightly, moderately, and heavily contaminated with $PM_{2.5}$ in Taiwan, respectively.

3.8. Quantifying People's Feelings of Haze Stress

Table 2 presents the mean and variance (SD) of hourly, daily, and monthly HSIs in the three cities during 2015–2018. The results show that the means and standard deviation of hourly, daily, and monthly HSIs in the three cities have been decreasing year by year, which is due to the effort of each city's environmental protection bureau to improve air quality in recent years. However, the effect of improvement is still small and needs to be further enhanced. Comparing between 2015 and 2018, the fractional reductions in the hourly, daily, and monthly HSIs in 2018 were 12.5%, 16.2%, and 18.4% in New Taipei; 7.3%, 8.8%, and 10.8% in Taichung; and 6.7%, 9.5%, and 11.3% in Kaohsiung, respectively. Thus, the effects of improvement in the three cities are in the following sequence: New Taipei > Kaohsiung > Taichung. It accurately reflects the current situation of the haze problem in the three cities.

Table 2. Summary of the mean and variance (SD) of hourly, daily, and monthly HSIs in the three cities during 2015–2018.

Cities	2015		2016		2017		2018	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
				Hourly HIS				
New Taipei	0.56	0.19	0.51	0.16	0.47	0.13	0.49	0.12
Taichung	0.55	0.25	0.55	0.24	0.51	0.19	0.51	0.19
Kaohsiung	0.60	0.34	0.55	0.38	0.62	0.33	0.56	0.27
				Daily HSI				
New Taipei	0.68	0.19	0.62	0.16	0.56	0.13	0.57	0.11
Taichung	0.68	0.25	0.68	0.24	0.67	0.18	0.62	0.18
Kaohsiung	0.74	0.34	0.68	0.38	0.75	0.31	0.67	0.26
				Monthly HSI				
New Taipei	0.87	0.12	0.79	0.16	0.71	0.09	0.71	0.09
Taichung	0.83	0.16	0.83	0.17	0.76	0.14	0.74	0.12
Kaohsiung	0.97	0.44	0.89	0.45	1.00	0.40	0.86	0.34

Note that New Taipei, Taichung, and Kaohsiung are the representative cities of slight, moderate, and heavy contamination in Taiwan.

Many countries experience severe haze pollution, especially in Asia. Li et al. [60] quantitatively examined the impact of public concern over haze by the utilization of an econometric model. However, people's feelings of haze stress are typically not quantified. There is still a lack of evidence on how haze stress affects people's mental and physical health [61]. Therefore, this study does not explore that people of different ages, genders, and living in different locations may have different feelings of haze stress. The values of four temporal HSIs were all distributed in a range between 0 and 2, and only a few values were greater than 2 (Figures 4–6). Additionally, their average values were between 0.5 and 1.0. So, a reasonable categorical method of people's feelings for determining haze stress is recommended, such as using an HSI grade with five scales (Table 3). Further, HIS = 1 is considered as the criteria between fair and anxious. The grade point ranges of the first four scales are all 0.5, and the grade point of the last scale is greater than two. Five descriptors of people's feelings were used (good, fair, anxious, uncomfortable, and very uncomfortable) to correspond to the individual HSI grades. The categorical method may help policy makers to understand the quantitative influence of haze, on the basis of which they may devise some effective countermeasures.

Table 3. Individual HIS and corresponding descriptors of haze stress indexes.

HSI	**0.0–0.5**	**0.6–1.0**	**1.1–1.5**	**1.6–2.0**	**>2.0**
Descriptor	Good	Fair	Anxious	Uncomfortable	Very uncomfortable

The percentages of five people's feelings for the hourly, daily, and monthly haze stresses in the three cities during 2015–2018 are shown in Table 4, which can be summarized as follows: (1) Different haze stress conditions caused by the degree of contaminated situations of city lead to a systematic variability of people's hourly, daily, and monthly feelings; (2) the sum of the three temporal people's feelings in good and fair in New Taipei City and in Taichung City were higher than 75% and 83%, respectively; (3) the lowest sum of the three temporal people's feelings in good and fair occurred in the monthly haze stress of Kaohsiung City (50.0% in 2015, 2016, and 2018); (4) people's hourly, daily, and monthly feelings in uncomfortable occurred most frequently in Kaohsiung City, especially in 2018; and (5) a low probability of people's hourly feeling in uncomfortable appeared in Taichung City in 2015–2018 (≤0.4%). Comparing the results with the frequency of people's struggles on the haze stresses in Taiwan, the data in Table 4 can truly reflect the feelings of people in the three cities.

Table 4. Summary of the percentages of five people's feelings (%) for the hourly, daily, and monthly HSIs in the three cities during 2015–2018.

People's Feelings	New Taipei			Taichung			Kaohsiung		
	Hourly	Daily	Monthly	Hourly	Daily	Monthly	Hourly	Daily	Monthly
				2015					
Good	43.1	12.9	0.0	52.4	27.4	0.0	47.8	32.3	16.7
Fair	53.9	80.3	75.0	41.7	61.6	83.3	38.7	44.4	33.3
Anxious	3.0	6.8	25.0	5.5	10.7	16.7	10.7	21.4	33.3
Uncomfortable	0.0	0.0	0.0	0.3	0.3	0.0	2.3	1.9	16.7
Very uncomfortable	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
				2016					
Good	53.3	24.6	0.0	49.6	27.0	0.0	54.4	39.9	25.0
Fair	45.7	72.7	83.3	45.3	63.7	83.3	32.8	37.4	33.3
Anxious	1.0	2.7	16.7	4.8	8.7	16.7	9.9	20.2	33.3
Uncomfortable	0.0	0.0	0.0	0.4	0.5	0.0	2.7	2.5	8.3
Very uncomfortable	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
				2017					
Good	67.5	34.5	0.0	56.3	31.2	8.3	41.7	28.2	16.7
Fair	32.2	65.5	100.0	41.6	63.8	91.7	45.2	49.9	33.3
Anxious	0.3	0.0	0.0	2.0	4.9	0.0	11.5	21.4	41.7
Uncomfortable	0.0	0.0	0.0	0.1	0.0	0.0	1.5	0.5	8.3
Very uncomfortable	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
				2018					
Good	60.6	25.5	0.0	56.6	30.4	0.0	48.2	33.2	16.7
Fair	39.1	74.2	100.0	41.2	65.5	100.0	44.8	54.5	33.3
Anxious	0.3	0.3	0.0	2.1	4.1	0.0	6.3	11.8	50.0
Uncomfortable	0.0	0.0	0.0	0.1	0.0	0.0	0.7	0.5	0.0
Very uncomfortable	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0

Note that New Taipei, Taichung, and Kaohsiung are the representative cities of slight, moderate, and heavy contamination in Taiwan.

The results in Tables 2 and 4 demonstrate that the HSI estimated using the inverse variance weightings method is highly consistent with the monitoring data and fully agrees with people's feelings.

4. Conclusions

Ambient haze mainly includes $PM_{2.5}$, SOA, and moisture. Therefore, the concentration of $PM_{2.5}$ cannot be used to express haze. Both government managers and people need a quantitative method to understand the effectiveness of improvement strategies and the public's feelings in the haze stress. This study proposed an approach for evaluating the HSI to quantify the effect of haze and the feelings of people in a region. The established evaluation method integrates three parameters—$PM_{2.5}$, RH, and O_3 + NO_2—with inverse-variance weighting to estimate the values of four temporal HSIs. The applied results for the slightly, moderately, and heavily contaminated cities in term of haze stress show that this method can achieve the goals. The estimated results of the improvement effects in regional haze can successfully reflect the current situation of the three cities according to their fractional reductions of ambient $PM_{2.5}$ (Figure 2) and HSIs (Table 2). Based on the frequency of people's struggles with the haze stress, it can also truly reflect the feelings of people in the three cities (Table 4). Therefore, the proposed method can successfully provide a quantification index of haze stress, thereby helping policy makers to understand the phenomenon of haze so that more stringent strategies can be implemented. This study presented a categorical method to analyze the effect of haze stress, which makes the quantitative results easier for people to understand.

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