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ORIGINAL PAPER

Quantifying the effect of rain events on outdoor thermal comfort in a high-density city, Hong Kong

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Abstract

Rainfall events often cause a modification to atmospheric conditions. The impact of this phenomenon on human thermal comfort has however been less well studied. Therefore, this paper quantifies the effect of rainfall events on human thermal comfort in a hot-humid subtropical city, Hong Kong. Firstly, rainfall events were categorized based on time of occurrence, i.e., morning (on or before 11:00 LST), afternoon (12:00–15:00, LST), early evening (16:00–18:00), and all-day events. Thereafter, human thermal comfort on typical non-rainy (sunny) days and rainy days was estimated and compared by using the radiation-driven physiological equivalent temperature (PET) and non-radiation-driven temperature-humidity index (THI) and compared. Results revealed variable and stable hourly patterns of PET and THI thermal classification, respectively under different rainfall event category. The insensitivity of THI values could be due to the retained strong contribution of both input parameters (air temperature and relative humidity) on both rainy and non-rainy (sunny) days. An understanding of the mechanism of thermal changes before, during, and after rainfall events based on statistical analysis suggests a strong interplay between moisture content and air temperature as determinants of thermal comfort in the hot-humid city and not necessarily the radiation parameter. This finding suggests that while PET clearly shows the impact of rain-event; it is principally due to the strong contribution of the lowered radiant temperature in its calculation while in reality, the critical determinants of thermal comfort in such period in a hot-humid subtropical environment like Hong Kong are the moisture content and ambient temperature. Finding from the study could enhance occupational health and safety management of outdoor workplaces.

Keywords Thermal comfort · Rainfall · Hot-humid · Summer · Hong Kong

Introduction

Meteorological parameters such as air temperature, relative humidity, solar radiation, and wind speed influence human thermal comfort sensation in urban outdoor spaces. Due to rapid urbanization and increasing intensity/frequency of climate change impact, levels of heat stress, urban heat island, and thermal discomfort have been worsening in summer months of several subtropical cities like Hong Kong (Cheung and Hart 2014). This has been raising occupational and public health concerns as heat-related mortality is increasing and productivity of outdoor workers is reducing especially in core urban centers or built-up areas (Yi and Chan 2015). To reduce this menace, previous studies had proposed several countermeasures such as urban greening, cool roof, water-retentive materials, modification of urban morphology, insulation of buildings, application of irrigation systems, and the inclusion of water bodies (Akbari et al. 2001; Ng et al. 2012; Santamouris 2014; Imam et al. 2017; Morakinyo et al. 2017a, b). However, very few studies have considered the effect of rainfall on thermal comfort in the urban built environment even though associated atmospheric conditions have a huge impact on our thermal environment. Incidentally, summer period, characterized with elevated temperature

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and solar intensity, is also the wettest period of the year with significant rainfall amount. Rainfall on its own is an atmospheric phenomenon that alters the thermal condition of our environment. This is due to three reasons: Firstly, prior to rain event is the formation of clouds of different types and mostly cumulus and cumulonimbus under calm and sunny weather conditions (Holton et al. 2003; Ahrens 2012) which results in convective precipitation as an aftermath of surface heating during the diurnal period (Charalampopoulos and Tsiros 2017). The cloud build-up guarantees abrupt changes in direct shortwave radiation, which consequently results in a reduction of surface temperature and bodily heat absorption through radiation. Secondly, due to lowered surface temperature and presence of precipitated water, air temperature ideally reduces during the rain event while the relative humidity increases, forcing lowered heat loss to perspiration. Lastly, due to atmospheric instability, wind speed is averagely higher around the rainy period; when wind condition is stronger, there is more evaporation by perspiration and greater heat loss from the human body. Hence, thermal comfort sensation varies before, during, and after an event. A common experience, however, is the feeling of increased human discomfort conditions after a storm during the warm/hot period. Few previous studies (Matzarakis and Moya 2002; Charalampopoulos and Tsiros 2017) have attempted to associate the effect of rain events on thermal comfort and/or heat stress. Matzarakis and Moya (2002) proposed the inclusion of precipitation information for the thermal indices to provide a complete picture of climate conditions and their significance in tourism climatology. The study thereafter presented a simple climate tourism index which includes precipitation for a tropical country namely Cuba. In the study, they applied rain duration as a rainfall indicator in the simple climate tourism index. There, rainfall duration was classified into five, ranging from "no precipitation" to one, three, six, and more than 6 h of precipitation. Charalampopoulos and Tsiros (2017) presented a preliminary assessment of the effect of rainfall events on human thermal comfort under hot weather conditions in Athens, Greece. They calculated the temperature-humidity index (THI) and physiological equivalent temperature (PET) of seventeen (17) rainy days in 2004–2015. Their results revealed that a rapid alteration of the PET index values after rainfall events occurs because of global radiation, air temperature, and relative humidity variations. The study, however, did not give an account of the effect of different time periods of the event and intensity of rainfall on the thermal comfort effect. Therefore, the present study aims at quantifying the effect of daytime (mostly convectional) rainfall and its associated thermal effects on human thermal comfort before, during, and after such rain events in Hong Kong. Specifically, this study seeks to provide answers to potent research questions such as the effect of time period of rain event on thermal comfort before, during, and after the rainfall event. Results could help determine the clothing and activity level on rainy days.

Study area, data, and methodology

Study area

The study area, Hong Kong, is situated along the coast of southeast China, characterized by a humid subtropical climate of hot and humid summer but mild winter. During the months of November and December, the sub-region is dominated with an abundance of sunshine, pleasant breezes, and cooler temperature while May to August is essentially hot and very humid with occasional showers and thunderstorms, particularly in the mornings. The afternoon temperature in this summer months can exceed 30 °C whereas, at nighttime, temperatures generally remain around 26 °C with high humidity. The total rainfall at the Hong Kong Observatory Headquarters (HKO) between 2010 and 2017 ranges between 1487 and 3066 mm, with about 80% of the rainfalls between the months of May and September. Climatologically, June and August are usually the wettest months while December and January are the driest months of the year.

Data description, selection, and filtering

This study uses hourly rainfall data of Sham Shui Po (SSP) weather station, air temperature, relative humidity, and wind speed of Hong Kong Observatory (HKO) headquarter station and global radiation and sunshine duration of King's Park (KSP) station for three summer months (June, July, and August) of 2013–2015. While it could have been perfect to have all datasets from the same station, some parameters were not measured in one or two of the stations within the period under consideration. Nevertheless, all weather stations are located in the densest district (Yau Tsim Mong) of the compact city (see Fig. 1); hence, the obtained datasets include the contribution of the built environment.

Following a data selection and filtering procedure, days with daytime (within the normal solar hour, i.e., 09:00–18:00 LST) rainfall event were selected and classified into four groups based on time period of the event, i.e., morning events (on or before 11:00, LST); afternoon events (12:00–15:00, LST); and early evening events (16:00–18:00, LST); and all-day event (i.e., rainfall signature all through the day). The motivation for this is the diurnal time series of direct shortwave radiation, which influences the magnitude of perceived thermal sensation. Rainfall event at any time along the profile will hypothetically have a significant effect on thermal comfortability before, during, and after the rain. To delineate the effect of these events on thermal comfort, thermal indices were calculated and averaged for

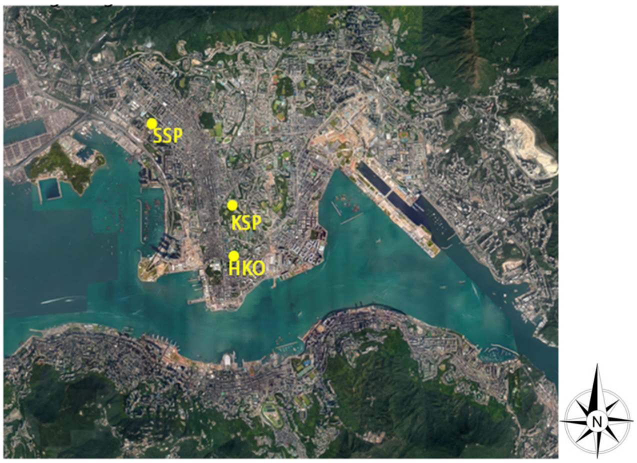

Fig. 1 GoogleEarth Imagery of part of Hong Kong showing the location of Hong Kong Observatory (HKO), King's Park (KSP) and Sham Shui Po (SSP) weather station

four (4) selected non-rainy days per month characterized by "fair weather" sky condition, i.e., relative daily sunshine duration[1] equals 0.8–1. Results were compared to that of rainy days in each month. Discussion of results attempts to detect and understand (if any) the relationship between rainfall intensity and duration and thermal comfort.

Methodology

To characterize the thermal comfort condition on reference and rainy days, two thermal comfort indices were applied, i.e., the radiation-driven physiological equivalent temperature (PET) and the non-radiation-driven temperature-humidity index (THI) also known as Thom's discomfort index (Thom 1959; Unger 1999). In a hot-humid and compact city as Hong Kong, humidity plays a crucial role in thermal comfort sensation across the city reducing the significance of shading in some instances; this effect is not duly captured in PET index because it is mainly driven by radiative fluxes. This motivated the selection of the non-radiation-based THI derived from air (dry bulb) temperature and relative humidity data only. THI has been said applicable for diagnosing thermal comfort in the tropical climates (Eludoyin and Adelekan 2013; Eludoyin et al. 2014; Chindapol et al. 2017). A detailed explanation of the derivation of THI has been well documented in Thom (1959), Kyle (1994) and Unger (1999). Herein, the mathematical formulation (Eq. (1)) and categorization (Table 1) given by Unger (1999) are provided.

Table 1 Temperature-humidity index (THI) thermal categories according to Unger (1999)

THI °C	Thermal category
13–14.9	Cool
15–19.9	Comfortable
20–26.4	Hot
26.5–29.9	Very hot
≥ 30	Torrid

$$THI = T_a - (0.55 - 0.055RH)(T_a - 14.5) \quad (1)$$

where

T_a air temperature (°C); and
RH relative humidity (%).

In addition, an energy balance–based thermal comfort index, physiological equivalent temperature (PET)[2] derived from the Munich energy model for individuals (MEMI) (Hoppe 1993) which has been prescribed to be a better and more acceptable (VDI 1998) thermal index was also adopted. This index considers radiation fluxes and their interaction with human body heat balance in the outdoor environment making it appropriate for assessing outdoor thermal comfort. This is because they are more relevant to human health as they have a closer connection with human thermoregulatory mechanisms and the circulatory system (Hoppe 1993; Höppe 1999; Matzarakis and Amelung 2008). To facilitate the calculation of PET, we employed the Rayman Pro model (Matzarakis et al. 2010) and thereafter classify the PET using Hong Kong's PET scale (Morakinyo et al. 2017b) (Table 2) for a standardized person (age 35 years, weight 75 kg, height 1.5 m; work metabolism: 80 W of light activity, and 0.9 clo of heat resistance) under an unshaded urban environment (Sky-view factor = 1).

In general, to quantify the effect of rain events on outdoor thermal comfort, Eqs.[3] (2a) and (2b) were adopted:

$$\Delta PET = PET_{ref,j} - PET_{i,j} \quad (2a)$$

where

ΔPET is the hourly relative change in PET when compared to a typical non-rainy(sunny) day;
$PET_{ref,j} = f(T_a, RH, WS \text{ and } MRT)_{ref,j}$ is the hourly PET on a typical non-rainy (sunny) day in the month j of the year 2013, 2014 or 2015.
$PET_{i,j} = f(T_a, RH, WS \text{ and } MRT)_{i,j}$ is the hourly PET on a rainy day of rain event type i = morning, afternoon, early evening, or all day in the month j of the year 2013, 2014, or 2015.

[1] Ratio of measured to extra-terrestrial possible sunshine duration.
[2] PET is equivalent to the air temperature that is required to reproduce in a standardized indoor setting and for a standardized person, the core and skin temperatures that are observed under the conditions being assessed (VDI 1998; Höppe 1999).
[3] WS is wind speed and MRT is mean radiant temperature.

Table 2 Physiological equivalent temperature (PET) range for different grades of human thermal perception and associated physiological stress in the tropics (Morakinyo et al. 2017b)

PET (°C)	Thermal perception	Physiological stress
26–30	Comfortable/neutral	No thermal stress
30–34	Slightly warm	Slight heat stress
34–38	Warm	Moderate heat stress
38–42	Hot	Strong heat stress
> 42	Very hot	Extreme heat stress

$$\Delta THI = THI_{ref,j} - THI_{i,j} \tag{2b}$$

where

ΔTHI, $THI_{ref,\,j} = f(T_a, RH)_{ref,\,j}$, and $THI_{i,\,j} = f(T_a, RH)_{i,\,j}$ have similar definition corresponding to PET above.

For each of rain event type, we investigated the ΔPET and ΔTHI before, during, and after the event and the result are fully discussed in the next section.

Results and discussion

Mean thermal comfort perception on non-rainy (sunny) summer day

Thermal comfort on a typical non-rainy (sunny) summer day in Hong Kong based on the radiation-driven PET is presented in supplementary file (Fig. S1 (a)). Between 19:00 and 07:00, *slightly cool* to *neutral* condition was observed irrespective of year and month between 2013 and 2015, which can be attributed to reduced shortwave radiation and lowered air temperature during this period of the day. The yearly variation revealed that 2013 was more comfortable (with more *slightly cool* sensation) at nighttime followed by 2014 while 2015 seems relatively more uncomfortable at nighttime under reference condition. This follows the pattern of annual total rainfall in these years; ~ 2850 mm, 2650 mm, and 1880 mm for 2013, 2014, and 2015, respectively based on Hong Kong Observatory database. This suggests that years with more rainfall activities are cooler than others even on sunny days. During the daytime when shortwave radiation is dominant, thermal comfort sensation ranges between *slightly warm* and *warm* condition. A similar pattern was observed for the 3 years under consideration; however, 2013 seems relatively more comfortable with less hour of *warm* condition especially in June and July, unlike other years. Generally, the above *neutral* condition began between 10:00 and 12:00, while *warm* condition occurred between 12:00 and 16:00 on non-rainy (sunny) days. Considering the non-radiation-driven THI, *very hot* condition dominated across every hour, i.e., no daily variation on non-rainy (sunny) days (see Fig. S1 (b)). The role of rainy weather on thermal comfort during the summer season will be discussed in the next section.

Mean thermal comfort perception on rainy summer days

Rainy days are often characterized by lower shortwave intensity, cloudiness, and higher humidity. As such, the thermal conditions on these days are expected to be relatively comfortable than non-rainy summer days. However, we hypothesized that the average hourly distribution of the thermal comfortability may be dependent on the time period of the rainfall (or cloudiness), duration, and intensity. Therefore, the further discussion will be relative to time period of the rainfall in comparison with a typical non-rainy (sunny) day thermal condition:

Morning events (occurring on or before 11:00)

This section gives an overview of temporal thermal comfort distribution on days with early morning (on or before 11:00) rain event as depicted in Fig. S2(a) and Fig. S2(b) for PET and THI index, respectively. During this period, shortwave radiation is normally not at its strongest intensity; therefore, thermal comfort based on PET index ranges between *slightly cool* and *neutral* condition albeit 1 h of *cool* and *slightly warm* condition was observed in June 2013 (at 6:00) and July 2014 (at 11:00), respectively. The main influence of the rain event (and its associated factors) resulted in more *slightly cool* hours and less *neutral* condition when compared to a non-rainy (sunny) days. This event also affected the thermal condition of the remainder of the day even though it was dry. However, the solar intensity across relatively reduced resulting in a more comfortable thermal sensation based on PET index of *slightly cool* to *slightly warm* condition between 12:00 and 18:00 on these days. With the THI index, early morning rain event resulted in slightly improved thermal condition during the event for some hours in 2013 and 2015, i.e., from *very hot* on non-rainy-sunny days to *hot* condition. However, no effect was observed during the post-event period (see Fig. S2(b)).

Afternoon event (occurring between 12:00 and 15:00)

During this period, solar radiation intensity normally peaks; therefore, rain event will expectedly result in a relatively more comfortable thermal environment when compared to non-rainy (sunny) day at the same time period. This is exactly the situation when assessed with the PET as depicted in Fig. S3(a). During this rain event, thermal comfort significantly improved from between *slightly warm* and *warm* on a typical non-rainy (sunny) day to between *slightly cool* and *slightly* *warm* conditions. In 2013, the maximum was *neutral* condition while "slightly warm" dominated in 2015. Also, pre and post-event thermal sensation were influenced; as more *neutral* condition was observed before 10:00 and 11:00 that is often characterized with *warm* thermal conditions on non-rainy (sunny) day. Similarly, post-event condition also improved from the usual *neutral* to *warm* condition to dominant *neutral* and "slightly warm." In terms of THI, there was no change in thermal sensation before and after the event especially during the daytime as the *very hot* was sustained during this rain event as it is for the non-rainy day (see Fig. S3(b)).

Early evening event (occurring between 16:00 and 18:00)

Rain at this time period resulted in *slightly cool* sensation for all months in 2013 and resulted in a low peak of *cool* thermal sensation in 2014 while the effect is weaker in July and August of 2015. Relative to non-rainy (sunny) days, this kind of rain event also impacts the thermal environment by reducing PET from between *neutral* and *warm* on non-rainy (sunny) days to between *slightly cool* and *warm*. The pre-event thermal sensation was also influenced as *warm* dominated hours were reduced to *slightly warm* or *neutral* conditions. In terms of THI, (see Fig. S4(b)) there were reduced hours of *very hot* especially in June and July due to the rain event. However, *hot* condition was still the minimum.

All-day rain event

This class of rain event is consecutive days of amber rainfall or tropical cyclone resulting in significant improvement of the thermal environment especially based on the PET index due to a notable reduction in solar radiation. In 2013–2015, thermal sensation ranges from *neutral* to *slightly cool* irrespective of time, month, and year (see Fig. S5(a)). There was also an improvement when THI classification was applied as *very hot* hours reduced drastically relative to reference days, although the minimal was *hot* in some months and hours while the maximum is remained *very hot* (see Fig. S5(b)).

Quantifying the effect of rain events on thermal comfort

Due to rain event characterized by cloudiness, lowered solar intensity, lowered temperature, and higher humidity, we have quantified the PET reduction before, during, and after each rain event and focus on the daytime impact. Here, we did not show similar result based on THI as the reductions are not sufficient to change the thermal class below *hot* in any case.

During morning showers, PET averagely reduced by 6.0 °C, 3.2 °C, and 4.0 °C in June, July, and August, respectively between 2013 and 1015. The range of ΔPET is − 8.6–(+ 1.1) °C, − 5.8–(+ 0.7) °C, and − 7.4–(+ 0.1) °C for 2013, 2014, and 2015, respectively. The positive effect of rain event is highest in June and least in July (see Fig. 2a).

After the morning showers, thermal sensation also improved as earlier discussed with ΔPET ranges between − 10.7–(+ 0.2) °C, − 6.8–(+ 2.3) °C, and − 9.1–(+ 0.5) °C in June, July, and August 2013–2015, respectively. This is equivalent to an average PET reduction of 6.2 °C, 4.1 °C, and 4.5 °C in June, July, and August 2013–2015, respectively indicating the greatest influence in June and least in July (see Fig. 2b). On the other hand, when assessed with THI (figure not shown), ΔTHI was − 2.8–(+ 0.1) °C, − 1.5–(+ 0.3) °C, and − 1.7–(+ 0.6) °C in June, July, and August, respectively during morning showers. This implies an average THI reduction of 1.5 °C, 0.8 °C, and 0.7 °C in June, July, and August, respectively. After the morning rainfall, ΔTHI was − 3.0–(+ 0.2) °C, − 2.3–(+ 0.4) °C, and − 2.9–(+ 0.2) °C in June, July, and August, respectively during morning showers. This implies an average THI reduction of 1.2 °C, 0.9 °C, and 1.0 °C in June, July, and August, respectively. With other categories of

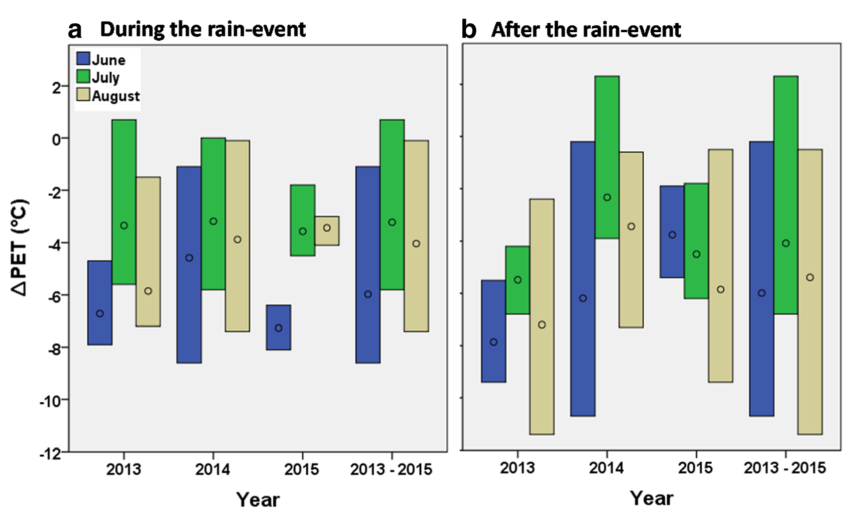

Fig. 2 Thermal comfort improvement **a** during and **b** after morning rainfall event based on PET

rain events, the ΔTHI is not significant enough as any combination of ≥ 24 °C and ≥ 70% will yield between *hot* and *torrid* thermal condition with or without rainy weather. This is the situation in our study irrespective of rainy condition and time of occurrence. Further discussion in this aspect will, therefore, be based on PET only.

The afternoon rain event likewise influences the thermal comfort levels before, during, and after; before this event (see Fig. 3), PET averagely reduced by 2.2 °C, 1.3 °C, and 1.5 °C in June, July, and August, respectively between 2013 and 2015. The ΔPET range is − 7.4–(+ 1.1) °C, − 4.1–(+ 2.0) °C, and − 4.6–(+ 0.9) °C June, July, and August of 2013–2015, respectively. The variance however reduced during the event with the higher magnitude of PET reduction; reduction ranges between − 11.0–(− 4.8) °C, − 11.8–(− 1.3) °C, and − 9.3–(− 0.3) °C in June, July, and August 2013–2015, respectively. This is equivalent to an average PET reduction of 8.0 °C, 6.9 °C, and 4.9 °C in June, July, and August 2013–2015, respectively indicating the greatest influence in June and least in August. Among the time periods considered, the maximum reduction was observed at the afternoon event simply because this is a period of maximum temperature and lowest humidity with notable shortwave radiation on a non-rainy (sunny) day. Therefore, modification of cloud condition at this time will yield a higher impact on the thermal environment on a rainy day. After the rain event, the thermal condition remains incomparable to that of the non-rainy (sunny) days with an average reduction of 4.0 °C, 3.4 °C, and 4.8 °C for June, July, and August, respectively in 2013–2015. The range is − 7.5–(+ 1.1) °C, − 7.4–(+ 1.2) °C, and − 9.6–(+ 2.0) °C.

Before the early evening events (see Fig. 4a, b), ΔPET ranges from − 9.4–(+ 0.1) °C, − 7.6–(+ 1.1) °C, and − 6.8–(0.0) °C which is equivalent to an average of 5.3 °C, 3.6 °C, and 3.6 °C for June, July, and August, 2013–2015, respectively. During the event, ΔPET ranges from − 9.4–(− 1.6) °C, − 12.5–(+ 1.7) °C, and − 13.8–(+ 1.8) °C or an average reduction of 6.3 °C, 8.6 °C, and 8.5 °C, for June, July, and August 2013–2015, respectively. For an all-day event (Fig. 4c, PET drastically reduces by up to 12 °C at a time of the day. Basically, the ΔPET ranges between − 14.7–(− 3.2) °C, − 13.2–(− 2.7) °C, and − 14.0–(− 7.1) °C for June, July, and August 2013–2015, respectively.

Predicting thermal comfort improvement on rainy days

We attempted to understand the contribution of each thermal parameter on improved thermal sensation before, during, and after rainfall. We achieved this by means of multiple linear regression (MLR) statistics as depicted in Table 3. The table provides MLR equations of ΔPET and ΔTHI before, during, and after rainy conditions with a corresponding correlation coefficient (R), the coefficient of determination, and significant influencer(s) at 95% confidence interval. An expected general observation is that rainfall, as a parameter, does not contribute to improved thermal sensation in any case which is because this parameter is not in the formulation of either of the indices. Beyond that, the intensity of rainfall does not show any significant impact on thermal condition but the length of the rain event produces cumulative positive impact as observed in "all-day" category. It is also interesting to note that irrespective of the thermal index, temperature and humidity are mostly the statistically significant influencer of thermal sensation during the most period which is consistent with theoretical understanding. The predictability of improved thermal sensation using the presented MLR equations indicates good performance ($R^2 > 0.7$) in most of the cases, while fair performance ($R^2 > 0.5$–0.69) was ound in some instance. The worst performance was with all-day (PET) whose $R^2 < 0.5$ where air temperature and wind speed with PET; however, relative humidity is equally important when THI was applied.

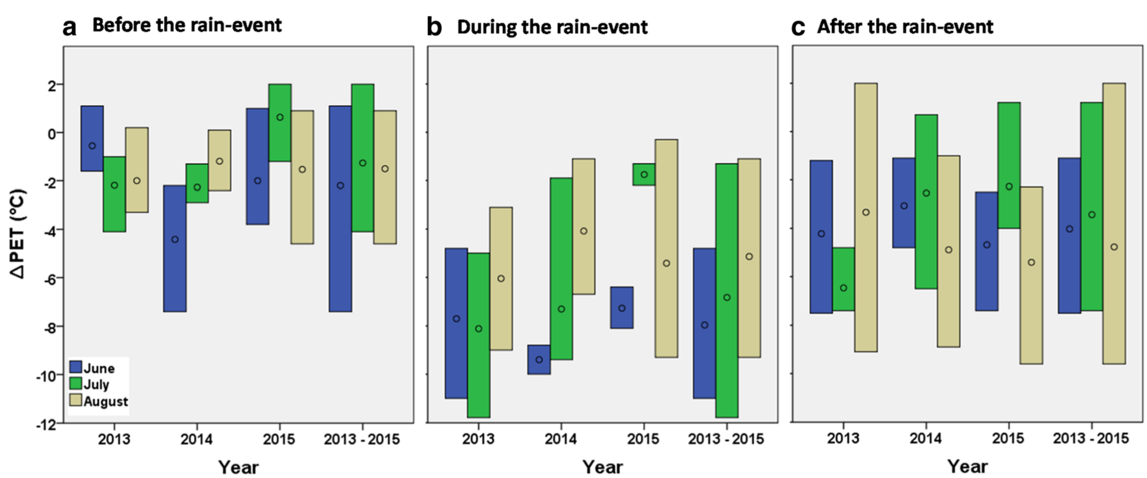

Fig. 3 Thermal comfort improvement for **a** before, **b** during, and **c** after afternoon event based on PET

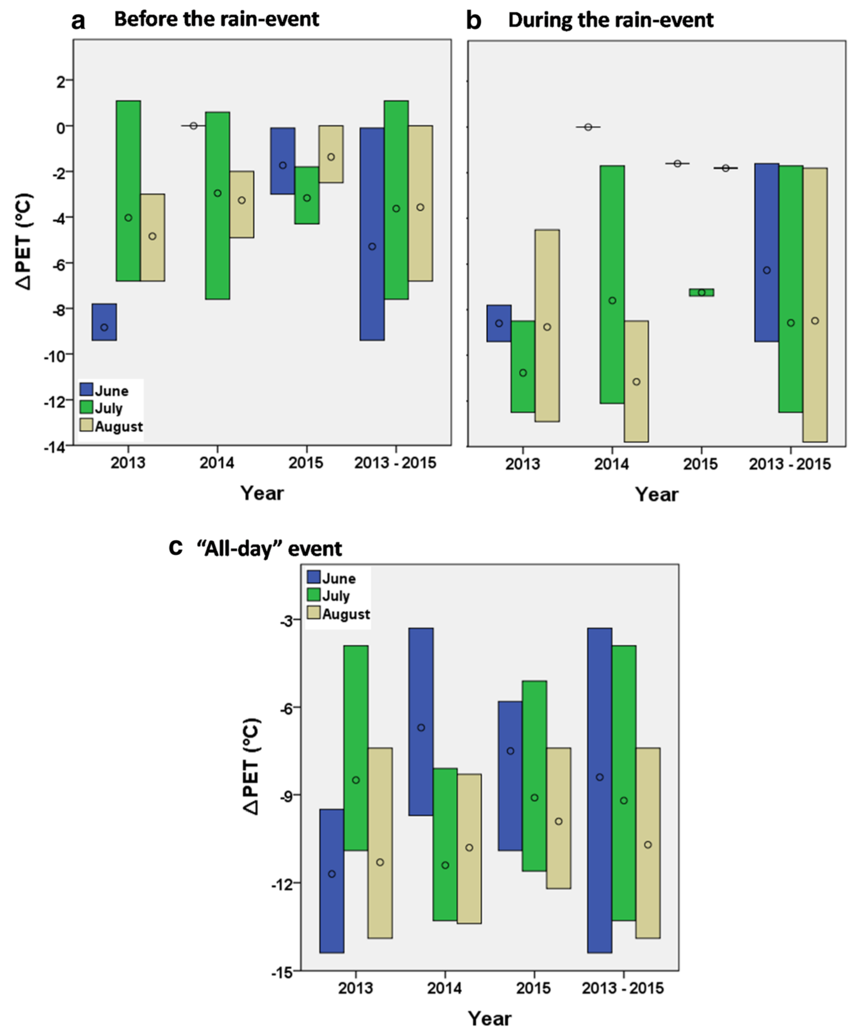

Fig. 4 Thermal comfort improvement **a** before and **b** during the early evening event, **c** "all-day" event

Mechanism of thermal changes before, during, and after rain events

Over the decades, it has remained debatable the type of thermal indices and what really captures perceived human thermal sensation. In recent times, the radiation-driven indices (such as PET) have been favored ahead of their non-radiation-driven counterparts (e.g., THI) mainly because the former is significantly dependent on the energy fluxes approaching a human body and believed to holistically capture human energy balance. However, the major driver of the radiation-driven indices is the mean radiant temperature, mainly determined by direct shortwave radiation during the daytime. Hence, before and during rain event when cloudy sky conditions prevail, the radiation-driven index indicates improved thermal comfort condition. This may not be the case subjectively, as other factors such as temperature and humidity dictate the thermal condition during this period, especially in the built environment. As depicted in the schematic below (Fig. 5), the urban environment is composed of fabrics that serve as immediate heat reservoirs, which absorb massive shortwave radiation and trap heat in canyons. Therein, conduction of heat between the surfaces (building and ground) and the environment occurs, thereby warming the overlying air. In addition, convection forces a proper mix of the air within the urban features. While rainfall is associated with cold gust that should ideally reduce ambient temperature, already trapped heat in canyons does not immediately compensate for this presumed change in heat due to the rainfall events, i.e., prolonged cooling rate. The thermal condition worsens in a saturated environment which cannot take any more moisture thereby prevent evaporative cooling and hence associated warmth even with rain event.

Generally, prior to a rain event, data revealed a relative reduction of the shortwave radiation due to cloudy condition, which implies reduced PET. However, the thermal sensation predicted by PET does not correspond to that of THI because of the highly humid (saturated) environment that prevents evaporative cooling either before, during, or after rain event. This type of phenomenon is more common in a highly humid environment like Hong Kong and can only be observed through a non-radiation-driven index like THI. With this index, our results revealed only *hot* and *very hot* situation

Table 3 Multiple linear regression model and statistics of thermal comfort improvement by on rainy days

Rain event/period	*N*	Multiple linear regression models	*R*	R^2	Significant contributor (at 95% confidence interval)
During ME (before 11:00)	47	ΔPET = − 3.1 + 0.65Ta–0.2RH − 0.47WS–0.0GR + 0.03RF	0.76	0.57	RH, WS
		ΔTHI = − 21.2 + 0.62Ta + 0.04RH	0.80	0.64	Ta
After ME (12:00–15:00)	76	ΔPET = − 31.8 + 0.8Ta + 0.2RH − 0.7WS + 0.02GR	0.91	0.82	RH, Ta, WS
		ΔTHI = − 29.7 + 0.77Ta + 0.08RH	0.91	0.83	RH, Ta
Before AE (09:00–11:00)	60	ΔPET = − 34.3 + 0.6Ta + 0.2RH − 0.6WS + 0.02GR	0.63	0.39	RH, Ta, WS, GR
		ΔTHI = − 32.2 + 0.7Ta + 0.13RH	0.84	0.71	RH, Ta
During AE (12:00–15:00)	35	ΔPET = − 36.2 + 1.0Ta–0.02RH − 0.28WS–0.02GR + 0.05RF	0.97	0.95	RH, Ta, WS
		ΔTHI = − 12.0 + 0.74Ta − 0.17RH	0.65	0.42	Nil
After AE (16:00–18:00)	59	ΔPET = − 63.1 + 1.9Ta + 0.03RH − 0.4WS–0.0GR	0.82	0.67	Ta, WS
		ΔTHI = − 36.8 + 0.92Ta + 0.02RH	0.85	0.73	RH, Ta
Before EEE (12:00–15:00)	36	ΔPET = 2.55 + 0.14Ta–0.15RH − 0.56WS–0.01GR	0.82	0.67	WS,GR
		ΔTHI = − 29.5 + 0.74Ta + 0.1RH	0.89	0.79	RH, Ta
During EEE (16:00–18:00)	19	ΔPET = − 66.9 + 2.28Ta + 0.01RH − 0.59WS–0.08GR	0.85	0.71	Ta
		ΔTHI = − 34.1 + 0.88Ta + 0.09RH	0.94	0.88	RH, Ta
All day	130	ΔPET = − 42.1 + 1.3Ta + 0.01RH − 0.47WS–0.01GR + 0.06RF	0.62	0.38	Ta, WS
		ΔTHI = − 36.4 + 0.93Ta + 0.1RH	0.87	0.75	RH, Ta

N, number of occurrence (Hr); *Ta*, air temperature; *RH*, relative humidity; *GR*, global radiation; *WS*, wind speed; *ME*, morning events; *AE*, afternoon events; *EEE*, early evening events

irrespective of rain event because the combination of at least ≥ 24 °C and ≥ 70% is always prevalent either in rainy or sunny conditions during the summer in Hong Kong. On the other hand, after a rainfall event (relative to during), PET value increases due to higher relative humidity and incoming radiation (Charalampopoulos and Tsiros 2017), which may in human discomfort if the changes are significant. This is with the exemption of after "early evening" rain event because an increase in incoming solar radiation is not feasible during the sunset hours. Hence, the intensity of the rainfall event and

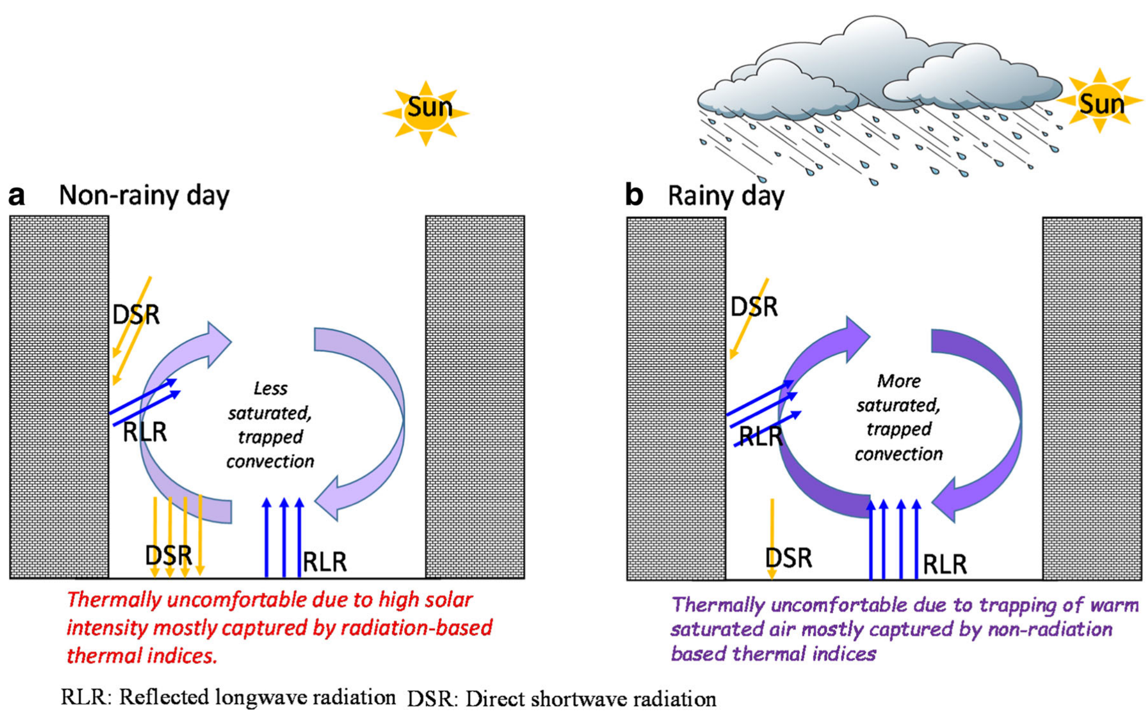

Fig. 5 Mechanism of thermal sensation on a rainy and non-rainy day in a built environment

the time of occurrence are other important features incorporated to this present study, in order to document their influence on human comfort before, during, and after rainfall events.

Conclusion

Using synoptic summer weather data of the year 2013–2015, thermal sensation on non-rainy (sunny) days and rainy days has been compared for an urban setting in a high-density city. The radiation-driven physiological equivalent temperature and the non-radiation-based temperature-humidity index were selected for the comparison. In addition, the relationship between rain event time of occurrence, intensity, and duration was investigated.

Depending on the time of occurrence, multiple linear regression models were able to predict improvement in thermal comfort with average correlation (*R*) of 0.82 and 0.84 for PET and THI, respectively. These changes in thermal comfort are driven by fluctuation in mainly by temperature and humidity while radiation and wind speed had a slight contribution in some cases. Even though the PET clearly shows the impact of rain event, it is principally due to the strong contribution of the lowered radiant temperature in the calculation while in reality, the critical determinants of thermal comfort in such period in a hot-humid subtropical environment like Hong Kong are the moisture content and ambient temperature. Findings of this study are useful in managing occupational safety and health in outdoor workplaces; clothing and activity levels should be determined with caution on days with rainfall signatures as temperature and humidity levels may rise to cause discomfort and dehydration despite lowered incoming solar radiation. To the best of our knowledge, this study is the first to investigate the relationship between rain event and human thermal comfort in a tropical climate. Results should be applied with caution as only the objective thermal comfort calculation approach was adopted. Future studies on this topic should aim to adopt subjective questionnaire survey method to corroborate the reported findings.

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