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Aerosol pollution and its potential impacts on outdoor human thermal sensation: East Asian perspectives

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ABSTRACT

Aerosols affect the insolation at ground and thus the Aerosol Optical Depth (*AOD*, a measure of aerosol pollution) plays an important role on the variation of the Physiological Equivalent Temperature (*PET*) at locations with different aerosol climatology. The aerosol effects upon *PET* were studied for the first time at four East Asian cities by coupling a radiative transfer model and a human thermal comfort model which were previously well evaluated. Evident with the MODIS and AERONET AOD observations, the aerosol pollution at Beijing and Seoul was higher than at Chiayi (Taiwan) and Hong Kong. Based on the AERONET data, with background *AOD* levels the selected temperate cities had similar clear-sky *PET* values especially during summertime, due to their locations at similar latitudes. This also applied to the sub-tropical cities. Increase in the *AOD* level to the seasonal average one led to an increase in diffuse solar radiation and in turn an increase in *PET* for people living in all the cities. However, the heavy aerosol loading environment in Beijing and Seoul in summertime (*AOD*s > 3.0 in episodic situations) reduced the total radiative flux and thus *PET* values in the cities. On the contrary, relatively lower episodic *AOD* levels in Chiayi and Hong Kong led to strong diffuse and still strong direct radiative fluxes and resulted in higher *PET* values, relative to those with seasonal averaged *AOD* levels. People tended to feel from "hot" to "very hot" during summertime when the *AOD* reached their average levels from the background level. This implies that in future aerosol effects add further burden to the thermal environment apart from the effects of greenhouse gas-induced global warming. Understanding the interaction between ambient aerosols and outdoor thermal environment is an important first step for effective mitigation measures such as urban greening to reduce the risk of human heat stress. It is also critical to make cities more attractive and enhancing to human well-being to achieve enhancing sustainable urbanization as one of the principal goals for the Nature-based Solutions.

1. Introduction

About 53% of world's population lives in cities (PRB, 2015). People in cities spend a significant time in outdoor spaces such as in parks and pedestrian streets. These spaces provide a pleasurable outdoor thermal comfort experience and effectively improve the quality of urban living (Chen and Ng, 2012). Therefore, the assessment of the thermal environment in urban open spaces has become increasingly important (Lee and Mayer, 2016). Urban planning and tourism - important elements of the innovative Nature-based Solutions - require an evaluation of the thermal component of different climates. The Physiological Equivalent Temperature (*PET*), according to Mayer and Höppe (1987),

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is one of the most popular thermal indexes used for this evaluation in the tropics and temperate areas (Johansson and Emmanuel, 2006; Andrade and Alcoforado, 2008; Mayer et al., 2008; Lin et al., 2010; Holst and Mayer, 2011; Hwang et al., 2011; Cohen et al., 2013; Krüger et al., 2014; Lai et al., 2014; Lee et al., 2013, 2014, 2016). It is based upon the Munich Energy Balance Model for individuals (Höppe, 1993), which models the thermal conditions of the human body in a physiologically relevant way. *PET* is a function of the meteorological variables mean radiant temperature (T_{mrt}), air temperature, water vapor pressure, and wind speed. They depend on the sky view factor (*SVF*) and ground cover. *SVF* is influenced by building shade (Mayer et al., 2008; Lin et al., 2010) and trees (Lee et al., 2013; Lee and Mayer, 2016; Tan et al., 2016).

Air pollution, especially aerosol pollution, is a major environmental risk to health (WHO, 2016). It is well documented that East Asia suffers from serious aerosol pollution (Wai et al., 2005b; Han et al., 2007; Kim et al., 2007; Cheng et al., 2008; Wai et al., 2008; Eck et al., 2010; Kim et al., 2014b; Chen et al., 2016). We focus attention in this study upon four major cities: Beijing, in China (urban population 18.6 M, area 1368 km^2), Seoul, in Korea (urban population 10.0 M, 605 km^2); Chiayi, in southern Taiwan (population 270,000, area 60 km^2) and Hong Kong, in southern China (population 7.2 M, total area 1104 km^2), refer to Fig. 1. The pollution in Beijing originates from Asian dust storm-derived mineral dust, emissions from other Provinces via long-range transport, and local industrial, dwelling and vehicular emissions (Han et al., 2007; Eck et al., 2010; Chen et al., 2016). The pollution sources for Seoul have some similarity to those for Beijing with additional influences from local large stationary sources and cross-boundary pollution from China (Kim et al., 2007, 2014a, 2014b). Chiayi and Hong Kong are relatively cleaner but suffer from local pollution and continental outflow of pollution in wintertime and springtime (Wai et al., 2005b; Cheng et al., 2008; Wai et al., 2008). It is well known that an increase of atmospheric aerosol loading enhances scattering and absorption of solar radiation and in turn reduces the solar radiative flux at ground level (Mitchell, 1971). At the same time the increasing aerosol loading also enhances the fraction of radiation which is diffuse (Greenwald et al., 2006). Therefore, a change in the aerosol optical depth (*AOD*, a measure of aerosol loading causing extinction of the solar beam) leads to a change in *PET* as mentioned. However, the important relationship between the two parameters has not yet been measured or modelled, and is not available in the literature as far as we know.

Therefore, we undertook a modelling study by using the thermal comfort software package RayMan (Lee and Mayer, 2016) and a radiative transfer model SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer Model), which are both evaluated to study the relationship. The summertime and wintertime *AOD* levels at the four studied cities were first characterized. As subsequently described, the aerosol impacts (in terms of *AOD* variations) on *PET* studied by the coupled SBDART model - RayMan software package were then

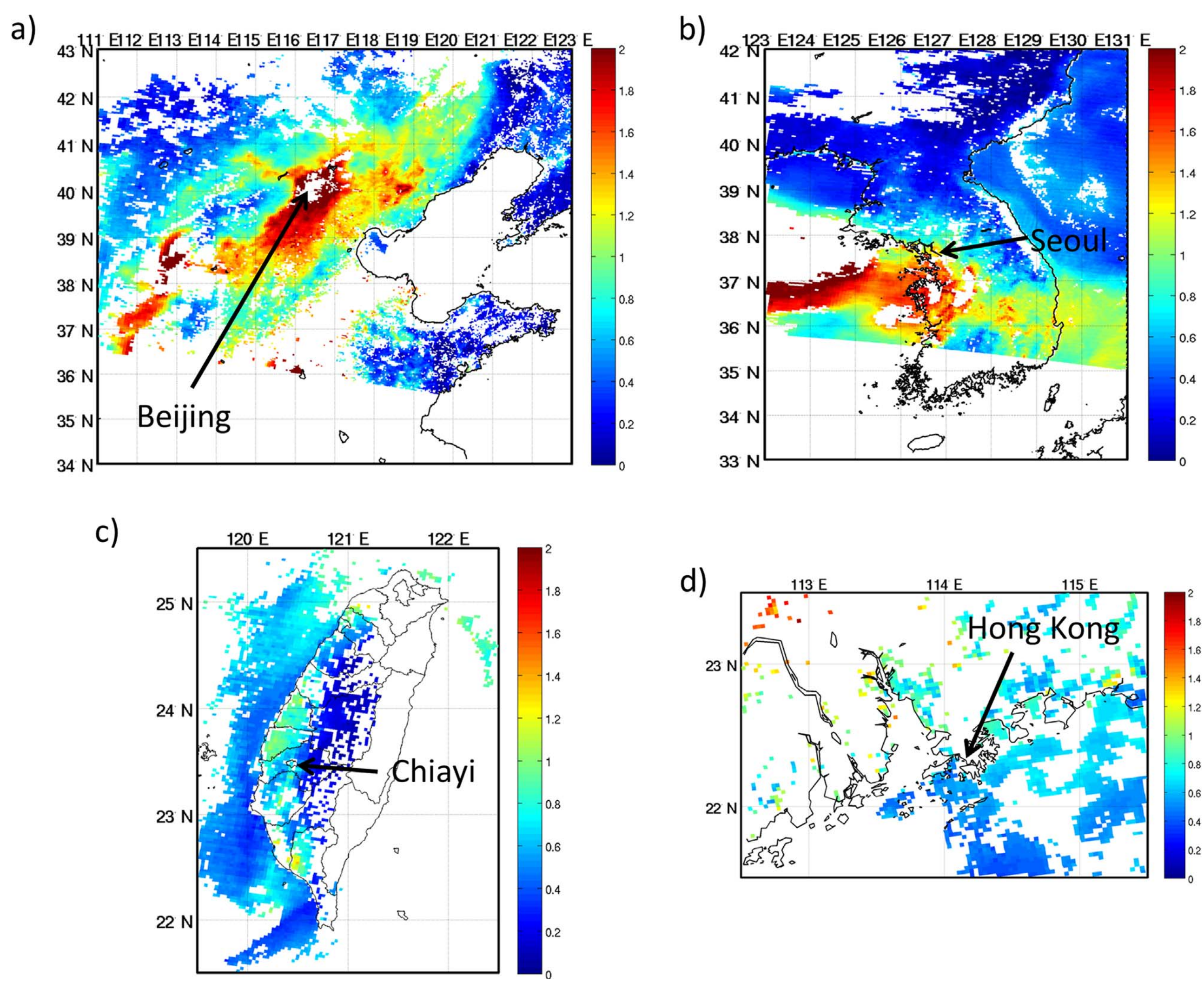

Fig. 1. The MODIS *AOD* (at 550 nm) distribution over the four studied cities and nearby areas: (a) Beijing (8 July 2015); (b) Seoul (20 October 2015); (c) Chiayi (17 January 2015); and (d) Hong Kong (20 March 2015). The *AOD* levels are colored (no data in white areas).

evaluated and discussed. Understanding the interactions between ambient aerosols and outdoor thermal environment is the important first step for effective mitigation measures, such as urban greening, to be implemented in order to reduce the risk of human heat stress. It is also critical to make cities more attractive and to enhance human well-being to achieve enhanced sustainable urbanization as one of the principal goals for Nature-based Solutions.

2. Methods

The Aerosol Optical Depth (*AOD*) Level 2.0 data at the wavelength of 500 nm from NASA's Aerosol Robotic Network (AERONET; https://aeronet.gsfc.nasa.gov/) were extracted. The description of measurement system, operation, calibration and quality control issues can be found elsewhere (e.g., Holben et al., 2001; Dubovik et al., 2002; Eck et al., 2005). The urban AERONET sites were located in Beijing (39.9°N, 116.3°E; at Chinese Academy of Meteorological Sciences), Seoul (37.6°N, 126.9°E; at Yonsei University), Chiayi (23.5°N, 120.5°E; at Chiayi meteorological station) and Hong Kong (22.3°N, 114.2°E; at Hong Kong Polytechnic University). We selected consecutive 12-month data for each site with a low percentage of missing data but only that for summer (Jun – Aug) and winter (Dec – Feb) months were included in the analysis (Table 1). The daily Level-2 AOD (at 550 nm) data with a 3 km spatial resolution observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites was also used.

The RayMan model (version 1.2) was adopted to calculate T_{mrt} and *PET* (Mayer and Höppe, 1987). The model has previously been employed and extensively evaluated for outdoor thermal comfort studies (Matzarakis et al., 2007; Thorsson et al., 2007; Andrade and Alcoforado, 2008; Lin et al., 2010; Hwang et al., 2011; Szűcs et al., 2014; Chen et al., 2014; Krüger et al., 2014; Lee and Mayer, 2016; Coccolo et al., 2016), although Lee and Mayer (2016) have shown that the application of RayMan within cities leads to results that are not reliable. The model description has been detailed in Matzarakis et al. (2007, 2010) and Lee and Mayer (2016). The global radiation and its ratio to diffuse reflected radiation were obtained from the radiative transfer model SBDART, which is subsequently described. Five-year averages of air temperature, relative humidity and wind speed measured at meteorological stations near (< 5 km) the AERONET sites were input into the model. The RayMan model inputs for these parameters were presented in Table 2. The wind speed at 1.1 m above ground is calculated by the following wind profile power law equation:

$$U_z / U_{ref} = (Z / Z_{ref})^{\alpha} \quad (1)$$

where U_z and U_{ref} are mean wind speeds at height Z and reference height Z_{ref}, respectively, and α is set to 0.25 which is a typical value used in the urban area (Lai et al., 2014; Tan et al., 2016). A person clad with clothing (0.9 clo) and having work metabolism (80 W) were taken as model defaults. The surface albedo of 0.1 was assumed, which is a comparable value in urban areas reported elsewhere (Vukovich, 1983; Ramachandran and Kedia, 2012; Wai et al., 2015). *PET* values at noon and clear-sky condition in summer and winter solstices were calculated.

Table 1
Summary of *AOD* values[a] at different AERONET sites.

	Beijing		Seoul		Chiayi		Hong Kong	
	SA[b]	Episodic	SA	Episodic	SA	Episodic	SA	Episodic
Summer	0.9	4.0	0.7	3.1	0.4	1.4	0.5	1.8
Winter	0.4	1.5	0.4	2.0	0.5	1.0	0.4	1.0

[a] Calculation based on daily averaged value. Data for Beijing (Oct 2014 – Sept 2015), Seoul (Jan – Dec 2014), Chiayi (Dec 2013 – Nov 2014) and Hong Kong (Mar 2012 – Feb 2013) were extracted.
[b] SA = seasonal average.

Table 2
Meteorological input data for RayMan model.

	Solar radiation[a] (W m^{-2})	Wind speed at 10 m above ground (m s^{-1})	Air temperature (°C)	Relative humidity (%)
Hong Kong				
Summer	997	1.7	28.1	83.5
Winter	702	1.7	16.8	71.6
Chiayi				
Summer	1010	2.0	28.8	77.1
Winter	686	2.0	17.3	78.5
Beijing				
Summer	963	3.3	25.9	67.5
Winter	441	4.3	−1.6	47.2
Seoul				
Summer	974	2.7	25.1	70.0
Winter	480	2.6	−0.8	54.9

[a] With background AOD level.

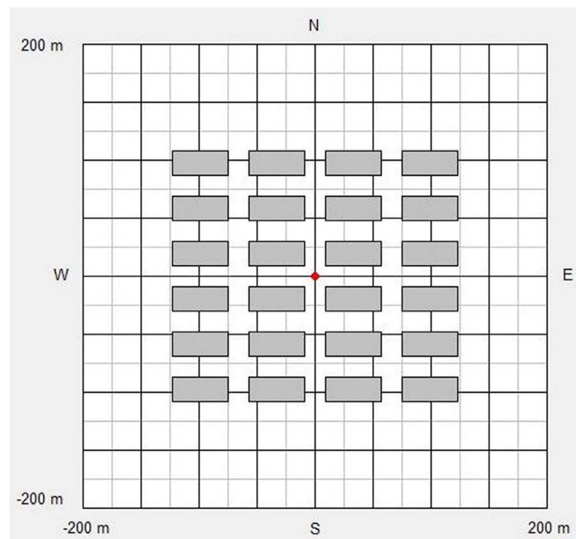

Fig. 2. Building block array for the *urban scenario*. The receiver is represented by a red dot. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Two scenarios were considered: (1) the "reference" with *SVF* of 1.00, and (2) the "urban" with *SVF* of 0.67. The latter assumed an array (6 × 4) of 10-storey (30 m height) buildings with each having a dimension of 48 m (L) × 21 m (W) (Fig. 2). Roads with width of 18 m were located in between the buildings (H/W ratio of 1.7). A pedestrian-level (1.1 m above ground level) receiver was located at the center of the building block array. The 10-storey building setting was used here such that the results, as discussed in the next Section, could be applied to other similar areas.

The direct and diffuse solar radiation in various *AOD* levels was calculated by the SBDART model (Ricchiazzi et al., 1998). The radiative transfer equation is numerically integrated by DISORT - a general purpose Fortran program for DIScrete Ordinate-method Radiative Transfer. The model has been used in many studies of solar radiative fluxes and aerosol effects upon the fluxes (e.g., Gautier and Landsfeld, 1997; Grenfell and Perovich, 2008; Valenzuela et al., 2012; Saeed et al., 2014). It has been evaluated with direct and diffuse radiative fluxes measurements and resulted in very small bias (< 2%) between modelled and measured values (Michalsky et al., 2006). Site specific *AOD* at 500 nm, single scattering albedo (ω) and the asymmetry parameter (*g*) were obtained as model inputs from the AERONET measurements. For the *AOD*, a value of 0.1 was considered as a reference level since it was the lowest value for all of the four study areas, similar to the situation elsewhere (e.g., Cirino et al., 2014). The seasonal average and

Table 3
Human thermal sensation categories for Beijing/Seoul and Chiayi/Hong Kong.

Thermal sensation	*PET* for Beijing/Seoul[a] (°C)	*PET* for Chiayi/Hong Kong[b] (°C)
Very cold	< −16	< 14
Cold	−16 to −11	14 to 18
Cool	−11 to −6	18 to 22
Slightly cool	−6 to 11	22 to 26
Neutral	11 to 24	26 to 30
Slightly warm	24 to 31	30 to 34
Warm	31 to 36	34 to 38
Hot	36 to 46	38 to 42
Very hot	> 46	> 42

[a] Lai et al. (2014).
[b] Lin and Matzarakis (2008).

episodic AERONET *AOD* levels for each site are summarized in Table 1. Annual averages for ω and *g* were adopted with the ranges of 0.92–0.97 and 0.67–0.71, respectively. The surface albedo was set at 0.1 as mentioned above. The model was executed for a tropical (mid-latitude) atmospheric profile for Hong Kong and Chiayi (Beijing and Seoul) using a 4-stream discrete ordinate radiative transfer solver (Yan et al., 2014).

The human thermal sensation categories reported for the study in Tianjin (39.1°N, 117.1°E; Lai et al., 2014) were used to evaluate the outdoor thermal comfort range for Beijing and Seoul, whereas those from the study at Sun Moon Lake (23.8°N, 120.9°E; Lin and Matzarakis, 2008) were employed for Chiayi and Hong Kong (Table 3). These represent the best information on *PET* categories available in the literature. Details of the survey (or questionnaires) and the methodology to obtain relevant micrometeorological parameters were described in the references and are not repeated here. The neutral *PET* range of 11–24 °C for the temperate cities was lower than that of 26–30 °C for the sub-tropical cities, indicating that humans in higher latitudes feels more comfortable in lower *PET* ranges, and vice versa.

3. Results and discussion

3.1. Characterization of the aerosol environment of the four sites

Fig. 1 shows the regional distribution of the MODIS *AOD* under episodic events (except at Hong Kong) and it demonstrates much higher *AOD* levels (*AOD* > 1.5) over Beijing and Seoul. The MODIS *AOD* levels were qualitatively consistent to those presented in Table 1 obtained from the AERONET data. Moreover, regional-scale rather than local-scale events are suggested. Therefore, the effects of episodic aerosol events on *PET* values discussed later were representative on a regional-scale. Although *AOD* levels over Hong Kong were not high in the figure, the aerosol pollution of the Pearl River Delta to the west/northwest of Hong Kong (i.e., an area with *AOD* > 1.0 in Fig. 1d) has major effects on Hong Kong when it is influenced by the land-sea breeze circulation (Wai and Tanner, 2005a).

In the temperate city Beijing, the AERONET seasonal average *AOD* summer level was higher than the level in winter (Table 1). This agrees with the findings of a long-term *AOD* analysis at two sites within and nearby Beijing (Chen et al., 2016). Our result is also comparable to that reported in a 10-year *AOD* study in Beijing (Eck et al., 2010). Interestingly, it is generally accepted that the poor "air quality" occurs in winter - rather than in summer - in Northern China (Qu et al., 2010; Tao et al., 2012; Miao et al., 2015). The discrepancy between the two scenarios was explained by the fact that poor "air quality" (or high air pollution index - *API*) is determined by PM_{10} concentration but not $PM_{2.5}$ concentration or fine-mode aerosols. The fine-mode aerosols (or fine-mode *AOD*) represent the major contributor in Beijing (Chen et al., 2016). The dominance of fine-mode aerosols features for most of the entire year even when peak advection of desert dust occurs from arid regions of western China towards Beijing during the spring months (Eck et al., 2010).

Similarly, at the other temperate city, Seoul, high AERONET seasonal average *AOD* occurred in summer (0.7) relative to winter (0.4), consistent with the *AOD* measurements in Seoul in 2013 by the Korean Meteorological Administration (Kim et al., 2014a). Using back trajectory analysis, these authors pointed out that the high aerosol loadings are due to weak advections during the summer months. Other reasons for the high summer levels include secondary aerosol formation by gas-to-particle conversion, hygroscopic growth of hydrophilic aerosols from enhanced atmospheric air moisture and the influence of biomass burning emissions in eastern China (Kim et al., 2007, and evident in Fig. 1c). Based upon the Community Multi-scale Air Quality (CMAQ) Model simulations, sulphate (formed from active photochemical reactions) was demonstrated to be the major contributor to summer *AOD* in Seoul (Park et al., 2011).

The AERONET summer-winter seasonal average *AOD* level differences for the two sub-tropical cities Chiayi and Hong Kong were small. The AERONET seasonal average *AOD* levels for these cities in the summer months were much smaller, due to the influences of clean maritime air masses, than those in Beijing and Seoul. The AERONET episodic *AOD* levels in the cities were also much lower than those of Beijing and Seoul, especially during the summer months, which might be due to the unfavorable effects of nearby high-emission sources in the latter cities. The AERONET *AOD* measurements in Chiayi were compared with the MODIS areal averaged *AOD* (at 550 nm, results not shown) for mid-Taiwan for the same measurement period. The MODIS summer (winter) averaged *AOD* of 0.5 (0.6) agreed well with the AERONET measurements. Similar averaged *AOD* levels in summer and winter months in the Pearl River Delta (including Hong Kong) to those of our AERONET results were also observed by the MODIS satellite in 2000–2010 (Luo et al., 2014).

3.2. T_{mrt} and PET at the four cities

Table 4 summarizes the calculated *PET* values at background, seasonal average and episodic *AOD* levels in summer and winter months for the four cities. Under the background *AOD* levels, people living in Beijing and Seoul felt "hot (or very close to hot)" in summer but only "slightly cool" in winter according to the thermal sensation categories shown in Table 3, irrespective of the "reference" or "urban" scenario. People living in Chiayi and Hong Kong felt "hot or very hot" in summer and "comfortable" in winter. *PET* for "urban" scenarios for the four studied cities had small increases (≤ 1.0 °C) compared to their corresponding "Reference" scenarios (Table 4), under the Background AOD situation. This is interesting since the buildings in the "urban" scenarios for the four studied cities were expected to reduce the diffuse solar

Table 4
Calculated *PET* values (°C) with different *AOD* levels for the "Reference" and "Urban" scenarios. The summer (winter) *PET* values are presented in the 1st (2nd) row for each city.

Background *AOD*		SA[a] *AOD*		Episodic *AOD*	
Reference	Urban	Reference	Urban	Reference	Urban
Seoul					
36.2	37.1	47.7	48.6	46.2	47.1
2.5	3.4	5.1	6.0	2.4	3.3
Beijing					
35.9	36.7	47.7	48.5	38.7	39.5
−1.7	−1.0	0.1	0.8	−1.5	−0.8
Chiayi					
41.9	42.8	49.4	50.4	60.3	61.2
27.9	28.8	35.3	36.2	36.6	37.5
Hong Kong					
41.5	42.5	53.0	53.9	62.9	63.8
28.8	29.7	34.8	35.8	38.9	39.8

[a] Seasonal average.

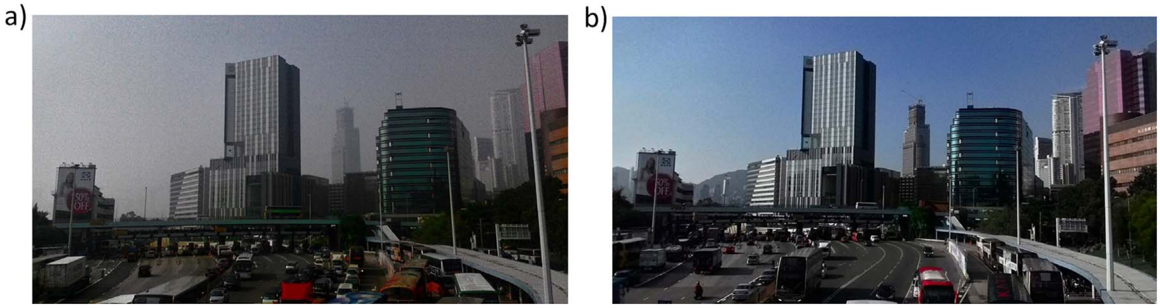

Fig. 3. A snapshot of the urban environment (in Tsim Sha Tsui) of Hong Kong at (a) high and (b) low *AOD* level.

radiation received and thus *PET* values at noontime. We attribute the slight increase in *PET* values for the "urban" scenarios to the building reflection and emission of longwave radiation to the receiver.

When the *AOD* increases, the solar radiation is more scattered by aerosols and thus the diffuse fraction (i.e., diffuse radiation divided by global radiation) increases. Various experimental studies have reported this phenomenon (Gueymard and George, 2005; Cirino et al., 2014; Shao and Zhang, 2015). However the total solar radiation (and the direct component) decreases with increasing *AOD* (Fig. 3). For instance in Beijing summer time, the SBDART model calculated total solar radiative flux at episodic *AOD* of 4.0 to remain at 30% of the background *AOD* radiative flux.

For the "reference" scenarios, *PET* values in all four cities increased with *AOD* levels when the latter increased from background to seasonal average *AOD* levels. However, further increase from the seasonal average to episodic *AOD* levels resulted in decreases in *PET* values at these two temperate cities. On the contrary, further increase from the seasonal average to episodic *AOD* levels at Chiayi and Hong Kong resulted in increases in *PET* values for these two sub-tropical cities. We used T_{mrt} to further analyze and explain the results since T_{mrt} has the strongest influence on *PET* in the daytime (Mayer et al., 2008; Holst and Mayer, 2011; Lee et al., 2013, 2014, 2016) and T_{mrt} is mainly controlled by direct and diffuse radiative fluxes (Lee et al., 2014). Chiayi and Hong Kong had much lower episodic *AOD* levels compared with the situations in Beijing and Seoul (Table 1). For such "moderate" *AOD* levels of the latter tropical cities, strong diffuse radiative flux in combination with relatively high direct radiative flux led to very high T_{mrt} values and thus *PET* values. Therefore in Chiayi and Hong Kong, *PET* values with episodic *AOD* levels were higher than those with seasonal average *AOD* levels. However for the situations in Beijing and Seoul, further increase in the *AOD* levels to episodic levels caused a rapid reduction of total (direct and diffuse) radiative flux although the diffuse fraction was high. This resulted in lowering the T_{mrt} values (and thus *PET* values) and could explain smaller *PET* values with episodic *AOD* levels than those with seasonal average *AOD* levels in Beijing and Seoul. A similar change in T_{mrt} with the ratio of diffuse/global radiation was reported in an open area using The Solar Long Wave Environmental Irrandiance Geometry model (SOLWEIG) model (Lindberg et al., 2014) which simulates spatial variations of mean radiant temperature and three-dimensional fluxes of longwave and shortwave radiation, although diffuse effects of cloud rather than aerosol were studied in that case. A small increase in *PET* was noted for the "urban scenarios" for all studied cities. The effects of the building reflection and emission of longwave radiation to the receiver were discussed earlier.

In summary when the *AOD* increased from background to seasonal average levels, higher *PET* values were calculated for both the "reference" and "urban" scenarios. When the *AOD* increased from seasonal average to episodic levels, *PET* values at Beijing and Seoul dropped. The effects were noticeable in Beijing in summertime (Table 4) so that people living there did not experience excessive heat under the situation with the episodic *AOD* level, relative to the situation with the background *AOD* level. On the contrary, summertime *PET* values in the sub-tropical cities Chiayi and Hong Kong increased rapidly with the *AOD* levels. For instance in the urban environment of Hong Kong during summertime, calculated *PET* with episodic *AOD* level was 21 °C higher than that with the baseline *AOD* level although both situations were classified in the "very hot" category. The situation with episodic *AOD* level is encountered when Hong Kong is located at the outskirts of a tropical cyclone (Wai and Tanner, 2005a, 2005b).

4. Concluding remarks

We have studied the impact of aerosol pollution on outdoor human comfort in East Asian cities. The study provided an important first step to enhance understanding of public health risk of heat stress and enhance human well-being as one of the principal goals of the Nature-based Solutions. The aerosol pollution in the two temperate cities was higher than at the two sub-tropical cities, as evident from satellite and ground observations. Generally speaking, people tended to feel from "hot" to "very hot" during summertime when the *AOD* reached the seasonal average levels from the background. It indicated aerosol pollution causing higher *PET* and therefore thermal discomfort situations more likely happen in cities which are hot and polluted during summer (except for the situation of episodic *AOD* levels for which *PET* could behave differently). At noon despite the building shading effects on diffuse radiation, *PET* at the urban center had a small increase due to the building reflection and emission of longwave radiation.

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