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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 (*AODs* > 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

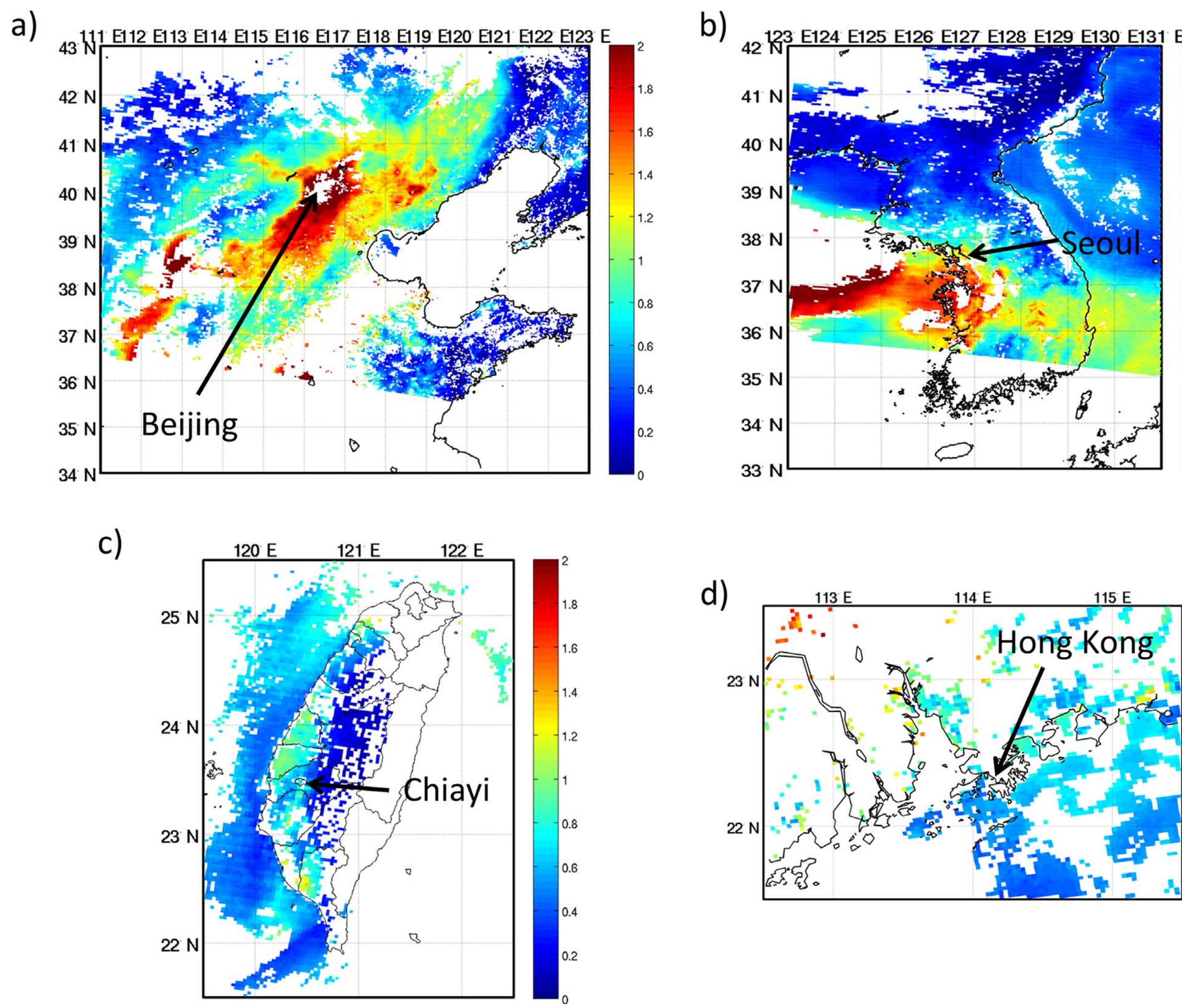

Fig. 1. The MODIS *AOD* (at 550 nm) distribution over the four studied cities and nearby areas: (a) Beijing (8 July 2015); (b) Seoul (20 October 2015); (c) Chiayi (17 January 2015); and (d) Hong Kong (20 March 2015). The *AOD* levels are colored (no data in white areas).