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Identifying outdoor thermal risk areas and evaluation of future thermal comfort concerning shading orientation in a traditional settlement

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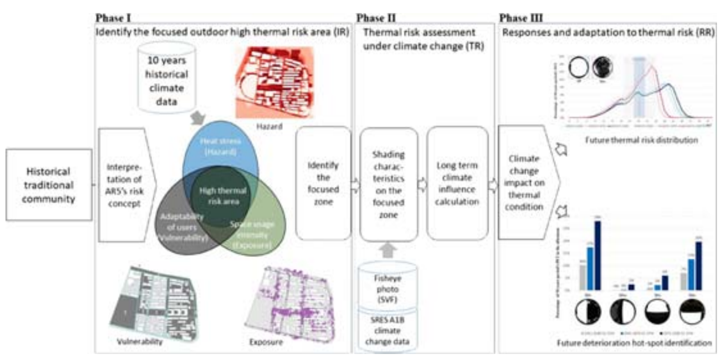
HIGHLIGHTS

- Hazard, exposure and vulnerability aspects were assessed to identify thermal risk in a traditional settlement in hot-and-humid Tainan, Taiwan.
- Hourly future climate data were constructed based on morphing method with GCM.
- Thermal stress map was produced by ENVI-met and future thermal comfort was simulated by RayMan.
- Maximum estimation of 168% increment of high outdoor thermal risk in the far future

GRAPHICAL ABSTRACT



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ABSTRACT

The outdoor thermal environment is expected to be deteriorated under climate change. An approach of risk identification including assessment from aspects of thermal stress effect, people's exposure, and local's vulnerability were adopted to study a hot-and-humid traditional rural community located at Tainan, Taiwan. Layers of each aspect were either constructed by in-situ measurements or simulations. To evaluate the future thermal comfort changes by simulations, the prerequisite hourly climate data of three future time slices were produced. Prognostic simulation model, ENVI-met, in combination with diagnostic model, RayMan, were respectively used for identifying current spatial distribution of thermal stress and for assessing the future thermal comfort changes. High thermal risk area was identified by superimposing layers of hazard, exposure and vulnerability. It revealed that because of the tourists' vulnerability to adapt local climate and the inflexibleness of choosing visiting time, it exhibited a high thermal stress at the Main Courtyard where its thermal comfort conditions will be deteriorated due to climate change. Furthermore, the thermal comfort conditions in various shading orientation were analyzed based on the changing climate in three future time slices, i.e. 2011–2040, 2041–2070, and 2071–2100. The results show the area with shading in the East and West side is more comfort than in the North side. In hot season, shading in the West side contributes less PET increasing, especially in the afternoon period. The severest overheat problem (the physiological equivalent temperature, PET > 40 °C) at the Main Courtyard will increase from current 10% to 28% in 2071–2100 in terms of overheating occurrence frequency. The results of this study can be used as the guidelines for environment analysis before planning or redesign community.

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1. Introduction

Anthropogenic activities would increase the emission of carbon dioxide resulting future climate change according to the report proposed by the Intergovernmental Panel on Climate Change (IPCC) in 2014 (IPCC, 2014). Previous study reveals that outdoor thermal environment perceived by a person will be affected by outdoor climate and the built environment (Lin et al., 2010). Less appropriate environmental design would also influence the conditions of microclimate and hence may jeopardize the thermal comfort. Therefore, how to formulate outdoor environmental design/planning by evaluating the outdoor thermal conditions under the context of climate change is the primary issue in this study.

Previous outdoor thermal comfort studies related to climate change are focused on outdoor environmental evaluation in perspective of urban context (Norton et al., 2015; Ren et al., 2012) or in terms of social-economic disaster mitigation (Csete et al., 2013; Moreno and Becken, 2009). Many thermal environmental studies aimed at community scale using climate change data for thermal environment simulation (Conry et al., 2015; Gromke et al., 2015; Lau et al., 2015; Loughnan et al., 2015; Peng and Elwan, 2014; Skelhorn et al., 2014), or performing comparisons between the measured and the simulated results (Cheung and Hart, 2014; Matzarakis and Endler, 2010; Muthers et al., 2010; Scott et al., 2015; Yang et al., 2015), or analyzing the actual environment with the observed and simulated meteorological data (Chen and Ng, 2011; Kuwae et al., 2004; Wang and Akbari, 2014). For those studies focusing on the issues of outdoor environment, the methods used by most researches are utilizing weather information, either measured or simulated, to discuss with shading ratio (Höppe, 1999; IPCC, 2000; Kruger et al., 2014; Lee et al., 2014; Lin et al., 2013b; Noro et al., 2015), human moving behaviors (Kantor and Unger, 2010; Nikolopoulou and Lykoudis, 2007), or with the thermal comfort of human body (Brosy et al., 2014; Lin and Matzarakis, 2008; Loughnan et al., 2015; Yang et al., 2013a; Yin et al., 2012).

Several studies regarding outdoor thermal comfort had been done in Taiwan: Hwang and Lin established the outdoor thermal comfort range for Taiwanese people (Hwang and Lin, 2007). Afterwards, outdoor thermal comfort studies and investigations focused on public square (Huang et al., 2015; Lin, 2009), urban parks (Lin et al., 2013a), school campus (Shih et al., 2017), and a rural traditional settlement (Yang and Lin, 2016) were extensively conducted based on the current climate conditions. However, the ambient air temperature increase rate of 0.81 °C per 25 years is observed in Tainan plain area under the influence of climate change (Lin et al., 2015). Another study on future urban heat island intensity (UHII) variation projection in central Taiwan area indicates that the UHII will increase to a maximum of 5.8 °C during 2075–2099 and, accordingly, will result in 476.9% increase in residential cooling energy use (Hwang et al., 2017). Furthermore, Lin et al. used the wet-bulb globe temperature index (WBGT) to evaluate future outdoor heat stress condition and found that it will be at danger level (WBGT > 31 °C) in summer months at the end of the 21st Century (Lin et al., 2017). All these studies show an imperative need to evaluate future outdoor thermal environment variation and formulate adaptation strategies to improve outdoor thermal comfort in facing with the changing climate to help resilience at community level.

The constraints of existing studies are as follows:

Firstly, none existing thermal environmental studies have analyzed both human usage behavior and their adaptability to the space. Many researches use single thermal index, such as physiologically equivalent temperature (PET) (VDI, 1998), to evaluate thermal conditions and user's adaptation of a given space regardless of the information such as the allocation and the degree of heat stress endurance of the space users. The understanding of the effect the micro-climate has on to a human is limited.

Secondly, single simulation tool cannot effectively fully demonstrate spatial and temporal distribution of micro-climate. Previous studies usually use one certain simulation tool as a method for evaluating outdoor thermal stress (Peng and Elwan, 2014), which it exhibits several limitations. Take general prognostic simulation tools (Loughnan et al., 2015; Yang et al., 2013a) for example, although spatial distribution of thermal conditions can be predicted and illustrated, due to computational constraints, it is not viable for presenting the thermal conditions results for a prolonged period of time. In contrast, although MRT of a given location point can be rapidly estimated by means of diagnostic model, such as RayMan model (Matzarakis et al., 2007a; Matzarakis et al., 2010), it is not capable for calculating spatial distribution of MRT across vast areas.

Thirdly, only thermal environment improvement of a given area is proposed in previous studies. A general hypothesis of the usage of a given space in previous studies is it always assumed that the human behavior is identical and is independent of time and the number of users, which usually results in proposing a universal layout design or material usage suggestions, such as increasing the greenery or changing the pavement material etc. (Matzarakis and Endler, 2010; Muthers et al., 2010). However, there are spaces where seldom people will use and is needless to be improved; or there are spaces where people will use during a specific time period or will be only gathered by certain groups of people. The adequate adaptation strategies should carefully be proposed by additionally considering the above different usage demands and limitations. By this means the adaptation strategies can be appropriately proposed and are able to be conveniently implemented to confront the impact of the changing climate.

Therefore, the objectives of this study in corresponding to the above three raised issues are:

1) To identify outdoor high thermal heat stress area in perspective of micro-climate risk assessment,
2) To evaluate thermal comfort condition in the thermal risk area based on various shading orientation, and.
3) To quantify daily, seasonal, and annually thermal stress condition and frequencies based on the future climate data.

2. Method

2.1. Research structure

To investigate the effect of climate change and the possible adaptation measures in terms of outdoor thermal risk, we followed the risk concept given in IPCC's the fifth assessment report (AR5). A previous study also adopted IPCC's risk assessment concept from hazard, vulnerability, and exposure perspectives in proposing a framework on the prioritization of green infrastructure allocation to alleviate UHI (Norton et al., 2015).

The research structure is as Fig. 1. In the first phase (IR) we firstly reinterpret the definition of hazard, exposure and vulnerability defined in IPCC AR5 to correspond to the assessment frame of local thermal for identifying the high thermal risk hot-spot in the studied community. The recognized hot-spot areas are the one we must prior focus on. In the second phase (TR), the existing outdoor shading locations in the hot-spot area were analyzed with the future weather data to investigate the influences on thermal comfort due to climate change. In the third phase (RR), the corresponding responses and adaptation measures were proposed in terms of hazard, exposure and vulnerability framework.

2.2. In-situ measurement and the environmental analytic tool

2.2.1. Investigation target and the research method

The research location is at Lutaoyang (N23°00′, E120°12′), where it is a historical traditional settlement in Tainan's suburban area with the altitude being 100 m, comprising about 3.4 ha with 160 m wide and 210 m long. The geographic location is as Fig. 2. Lutaoyang, where is a