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Study on human thermal comfort for architecture – The Example of Shanghai, China

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1. Introduction

Community environment design, as an important branch of urban design, focuses mainly on producing and performing a design proposal for an area. Thereby this area could be modified through increasing green space, forming bodies of water, or equipping shading facilities. The human thermal comfort conditions will certainly be influenced in these series of processes.

Thermal comfort, which is an important issue in human-biometeorology, describes the degree of satisfaction of the human body in a thermal environment (Fanger 1970; Fanger 1973; ASHRAE 2001). Extremely uncomfortable thermal conditions will result in high risk illnesses, e.g. sunstroke. Thermal environment could be improved effectively by reducing the short wave radiation (Lin 2009) and increasing ventilation (Chen et al. 2004) in the thermally uncomfortable areas. The Physiologically Equivalent Temperature (PET) (Mayer and Höppe 1987; Höppe 1999; Matzarakis et al. 1999), as a widely used thermal index, could indicate how human beings sense the actual thermal environment by values with Celsius as the unit.

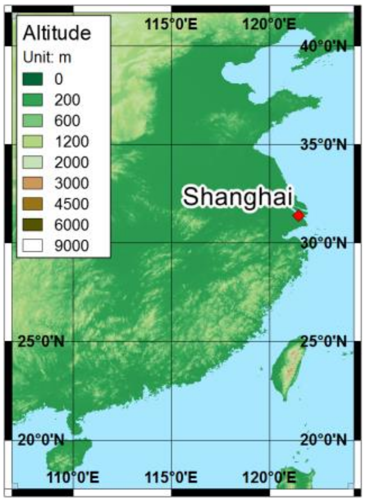

Fig. 1 Position of Shanghai

The thermal comfort conditions of a city are influenced by the locally meteorological conditions through the year round. In other words, there are regular conditions existing in a long-term period. Paying attention to high-risk periods, for instance the hottest month in of a year, would identify the extremely thermal conditions. Meanwhile, multiple thermal conditions (comfortable or undesirable) are present even in a small urban district. Therefore, the identification of different thermal comfort areas in one district is important for community environment design. However, the challenge is how to locate, and then to evaluate the thermal comfort conditions of the designed area. For that reason, short-term numerical simulation of the micro meteorology could be one possible methodology for architects and urban planners to identify the particular area in the analysis phase of design.

Fig. 2 A bird's-eye view of community environment design of one residential district

Shanghai (*Fig. 1*) is one of the most famous mega cities not only in China, as well as the world. Various issues relating to urbanisation in mega cities are prevalent, especially the issues on human healthy and urban planning. In China, the high-rise buildings constitute as one of the necessary building styles, which are developed for residential districts and commercial streets in mega cities (Gaubatz 1999; Chen et al. 2008). The urban area in Shanghai has mainly been constructed with high-rise buildings for the past few decades (Tang et al. 2008; Yang et al. 2010). This building style strongly influences the micro meteorological conditions in urban area (Oke 2006). However, until now, it rarely utilised the knowledge on human thermal comfort to modify the outdoor recreational space. The study on thermal comfort in one representative mega city, can offer possible solutions for these issues directly and efficiently. Therefore, taking Shanghai (meteorological background) as an example for community environment design can offer not only the representative thermal comfort conditions in Shanghai, but also the effects of the high-rise building district on micro biometeorological conditions. This method can also be applied for other cities, i.e., other meteorological backgrounds.

The objectives of this study are (1) to analyse the thermal conditions in the long-term period based on the meteorological data of Shanghai, and (2) to evaluate the thermal comfort conditions in the residential district based on the short-term micro biometeorological data from simulation.

2. Data and Methods

In this study, a community environment design for a hypothetical residential district has been selected with meteorological background in Shanghai. In this district, the main building style is the high-rise building. *Fig. 2* presents the community environment design which is mainly based on forming green space in between the buildings. Due to the commercial purpose, the bird's-eye view of the district has been decorated with a body of water and forests, which are both fictitious. Thus, in practice, the community environment design is only performed in between the constructed area, i.e., nearby the buildings and along the commercial street. This design will be used as a comparative case in terms of results and analysis.

The long-term meteorological data (3-hour intervals in 2000-2012) of Shanghai has been downloaded from http://www.ogimet.com. Air temperature (T_a), relative humidity (*RH*), cloud cover (c) and wind velocity (*v*) have been used for calculation of PET, together with local standard time (LST). The points in time are 2 LST, 5 LST, 8 LST, 11 LST, 14 LST, 17 LST, 20 LST and 23 LST. The RayMan model (Matzarakis et al. 2007, 2010) has been applied to calculate PET, in order to analyse the actual and long-term thermal conditions in Shanghai. T_a and PET have been categorised with different classes based on a classification of thermal sensitivity for moderate climates (Matzarakis and Mayer 1996) by monthly frequencies. The hottest conditions have been identified in this stage.

In order to form initial atmospheric input data for a short-term simulation (48 hours), a set of typical meteorological data of one day has been prepared based on the data in July of each year (2000-2012). This input data is hourly T_a and hourly *RH* of 24 hours, which have been both calculated through weighted mean values based on the 3-hour data in July. The most frequent wind direction and mean wind speed in July have been both calculated using the 3-hour data in July.

The short-term simulation has been accomplished through the application of the ENVI-met model (Bruse 2004; Bruse and Fleer 1998; Huttner et al. 2008). For the step of drawing a simulated area, a street valley has been constructed by adding the same buildings on the other side of the commercial street (compared to *Fig. 2*). This modification has made the residential district more representative. The 3-D space in the simulation has been set with parameters of 340 × 340 m^2 horizontally, and 100 m vertically. 2-meter resolution has been set in the direction of x (horizontal) and y (horizontal), as well as 3-meter resolution in the direction of z (vertical). Each high-rise building is 66 m in height. The buildings, which form the commercial street valley, are 10 m in height. Hourly micro biometeorological conditions of this residential district have been obtained through a 48-hour simulation. The simulation in the first 24 hours is used to form a stable atmospheric environment, therefore the simulation in the second 24 hours has been utilised for analysis. Finally, hourly x-y cut figures (z: 0-3 m) on PET values have been obtained from the simulation. After comparison, the hottest condition has been found at 14 LST. PET values have been illustrated with a new set of value classes, which present a much warmer distribution than that in the classification of thermal sensitivity for moderate climates. According to the figure at 14 LST, the undesirable thermal-comfort areas in this design district have been detected.

3. Results and Analysis

3.1 Long-term thermal comfort conditions

Fig. 3 contains 6 figures in total, which present the distributions of T_a values and PET values by monthly frequencies at 11 LST, 14 LST and 17 LST in 2000-2012, respectively. Both of this two parameters are categorised by 9-value classes, which are from the classification of thermal sensitivity for moderate climates (Matzarakis and Mayer 1996).

Hottest month: In the conditions of both T_a and PET, the highest frequencies of the hottest classes appear in July. This can be observed at three points in time. T_a (29-35 °C & 35-41 °C) at 14 LST appears approximately 80 % days in July in these years, and no value is higher than 41 °C. PET (35-41 °C & > 41 °C) at 14 LST appears more than 80 % days in July. PET values are higher than T_a values in July. Meanwhile, the frequencies of PET values change noticeably from month to month. Hence PET, as a sensitively thermal index, distinguishes thermal comfort conditions more straight than T_a. In general, July can be regarded as the hottest period in Shanghai during 2000-2012.

Hottest point in time: Through the comparisons between 3 groups figures at 11 LST, 14 LST and 17 LST, it could be found that the frequencies of warmer classes of T_a in each month increase from 11 LST to 14 LST, and decrease from 14 LST to 17 LST. The frequencies of PET in different classes at 11 LST and 14 LST are similar, but the frequencies of warmer classes of PET decrease from 14 LST to 17 LST sharply in each month. Since the obvious peak value of T_a appears at 14 LST, it is the hottest point in time.

3.2 Preliminary simulation analysis

The initially atmospheric data of one typical day in July (2000-2012) is presented in *Fig. 4*. The highest T_a (31 °C) appears at 14 LST, and the lowest T_a (27.1 °C) appears at 5 LST. In contrast, the peak value and the valley value of *RH* are the other way round: maximum *RH* (83 %) is at 5 LST, and minimum *RH* (64 %) is at 14 LST. Based on 16 cardinal directions, ENE has the highest frequency of wind direction in July. The mean wind speed is 3.1 m/s in the same period. The simulation is limited by this dataset.

Since T_a has not taken other factors into account which influence thermal comfort conditions, the amplitude of T_a in this typical day is small (less than 5 °C). It will result in a much weaker amplitude in one hour of the spatial simulation, which indicates the homogeneous thermal environment in this area. Actually, the thermal comfort conditions are numerous in micro meteorology.

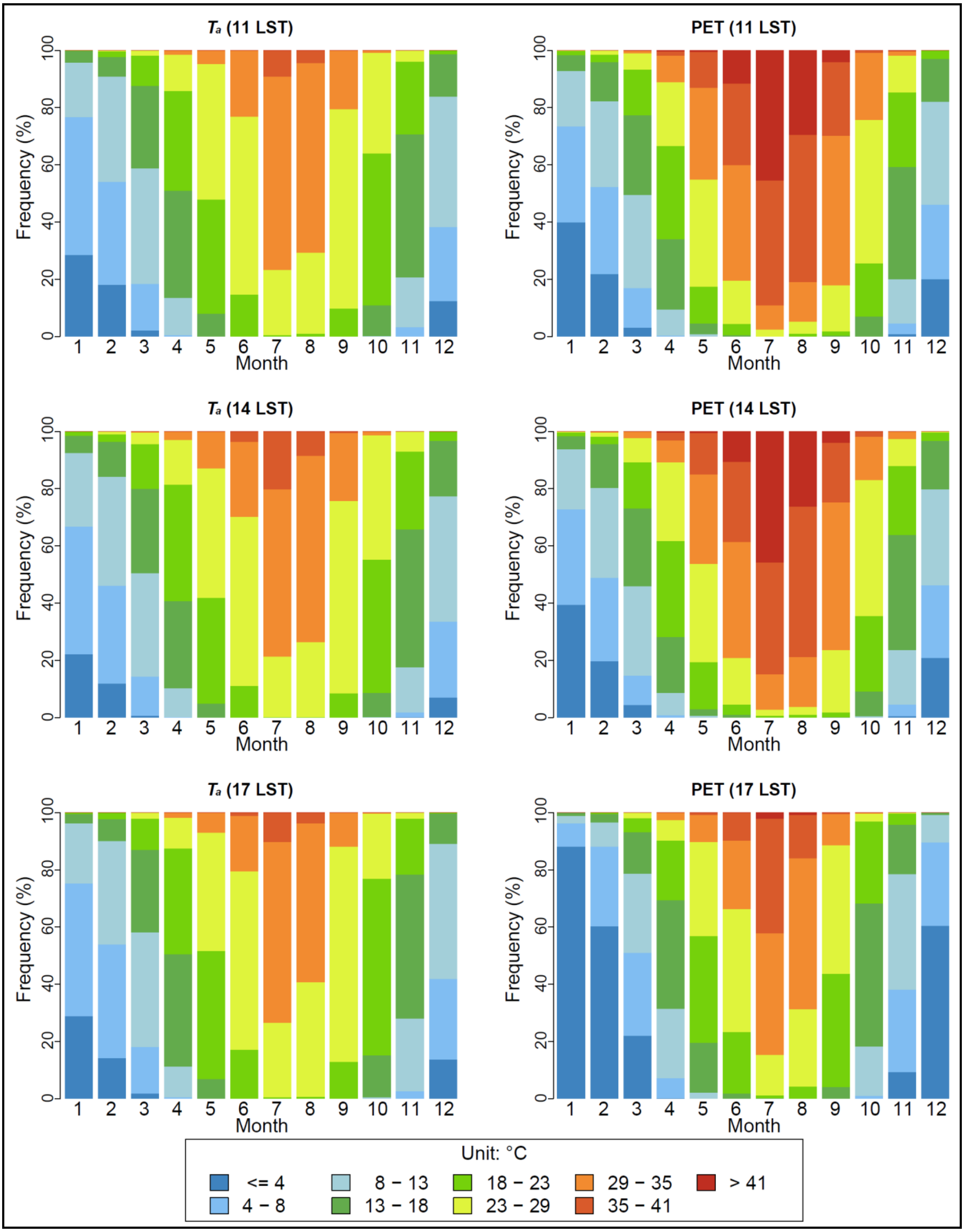

Fig. 3 Monthly frequencies of T_a and PET with different classes at 11 LST, 14 LST and 17 LST, respectively

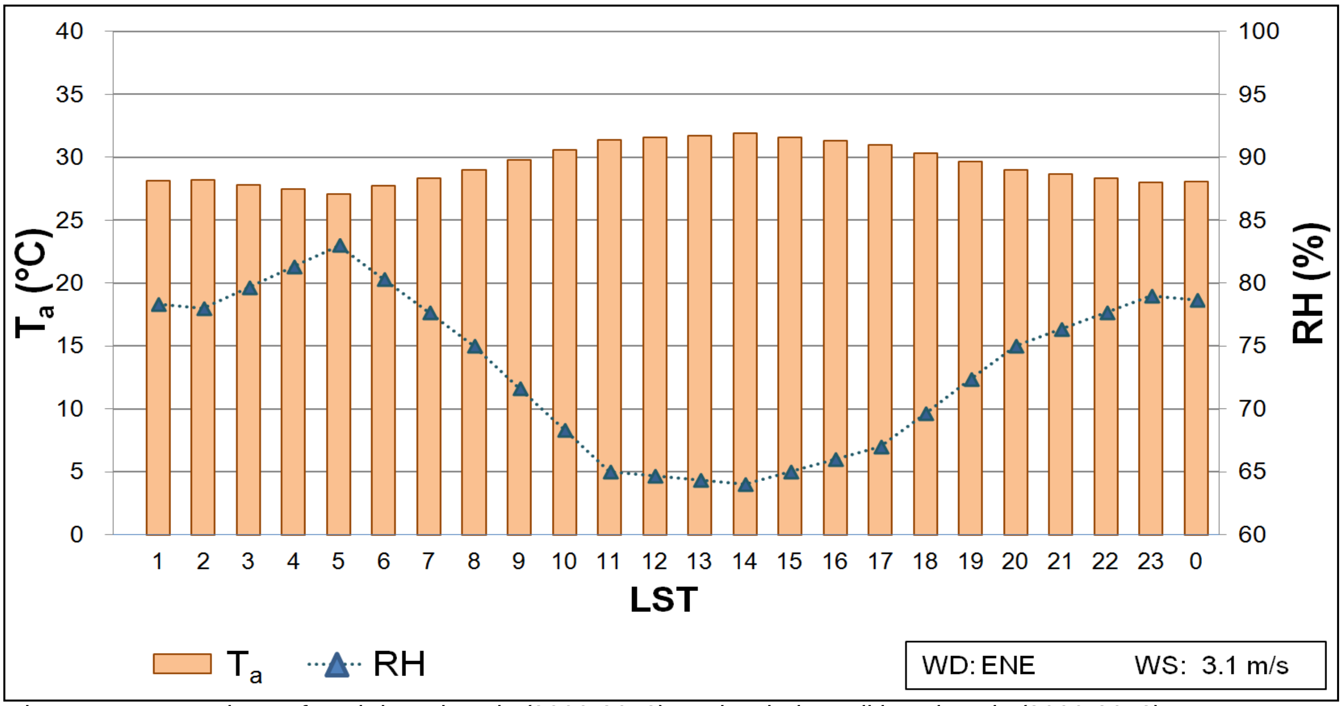

Fig. 4 Mean T_a and RH of each hour in July (2000-2012); main wind conditions in July (2000-2012)

3.3 Simulation of thermal comfort conditions

In order to evaluate the spatial differences of thermal comfort conditions of this district on a micro meteorological level, PET was selected as the final indicator to show the simulation results. The thermal comfort conditions at 14 LST of this district (340×340 m^2) shown in *Fig. 5*, which are the hottest conditions compared to the other points in time. The white part in *Fig. 5* represents building area on x-y cut direction, while the other colours stand for PET in different value classes (compared to the legend in *Fig. 5*). Combining the north arrow in the figure, the hottest areas can be observed along the southwest side of the buildings at 14 LST with PET higher than 54 °C. At the same time, the coolest areas are detected along the northeast side of the buildings with PET in 29-41 °C. There is no area with PET lower than 29 °C.

The first reason for this spatial distribution of PET values is direct short wave radiation. The hottest areas (PET > 54 °C) are along the sides of buildings where sunlight can arrive directly, while the coolest areas (29 °C < PET <= 41 °C) are in the shadows. The second reason is wind direction and wind speed. The distribution of the hottest areas (PET > 54 °C) is towards WSW, which is the opposite direction of the main wind direction ENE. The obvious effect could be tracked along the pedestrian street and the single high-rise buildings along y(20-30) in *Fig. 5*. Due to the obstacle effects from buildings, the wind speed is reduced dramatically for the nearby buildings. Therefore, the PET further increases in these areas due to less air turbulence. The influence of reflected short wave radiation and long wave radiation from the environment are the third reason for the thermal condition distribution. Due to these two factors, the values of PET around buildings are higher than that of open areas.

Comparing *Fig. 5* with *Fig. 2*, the unsuitable positions of trees are easily to be found along the commercial street in *Fig. 2*. Trees have two main effects on thermal environment, which are reducing the direct short wave radiation by canopies (Matzarakis et al. 1999; Streiling and Matzarakis 2003) and weakening the ventilation (Oke 2002) around themselves. In the community environment design in *Fig. 2*, the trees are planted far from the hottest areas, where there is an actual need for the shading effects from trees. Meanwhile, the trees also act as obstacles in *Fig. 2*blocking the important ventilating path along the southwest side in this street valley, i.e., in the area of y(50-70). Meanwhile, considering the economical purchase of plants, the density of trees in the coolest areas can be reduced. This will also contribute to increase the ventilation in the area of y(100-140).

4. Discussion

In order to prepare a reliable and typical meteorological input data for a short-term numeric simulation, the long-term data analysis is necessary to identify one special period. The analysis of monthly frequencies could show the actual thermal comfort conditions in the past years (a long-term period). Although July has been chosen as the represented hottest period in this study, ten-day time scales in one year could be also applied in the future, which will present meteorological characteristics in a more precise time period.

The short-term simulation by ENVI-met model presents theoretically micro meteorological conditions of the simulated area. These could be regarded as the typical conditions; however, the results would not represent exactly the actual thermal environment of the area. Thus, simulation by ENVI-met model is currently regarded as a possible methodology to detect the location of specific thermal comfort conditions. Moreover, the possible range and resolution of the three dimensions (x, y, and z) in this model limit the quality of the drawing area. This leads to the relative low accuracy of building shape. Fortunately, as ENVI-met model is keeping updated, the limitation of drawing area may be improved in the future. In general, the simulation results can already track the specific thermal comfort areas based on the typical input data.

From the results, four recommendations could be obtained for architects and urban planners, in order to design a more comfortable micro biometeorological environment. First of all, if possible, a long street valley should be located along the main wind direction, in order to maintain good ventilation. Secondly, it is suitable and necessary, in the hottest areas, to increase shade by planting trees or setting up other shelters. Thirdly, the position of trees should avoid the ventilating path. Fourthly, the density of trees in the coolest areas could be reduced, due to the low requirements for shading.

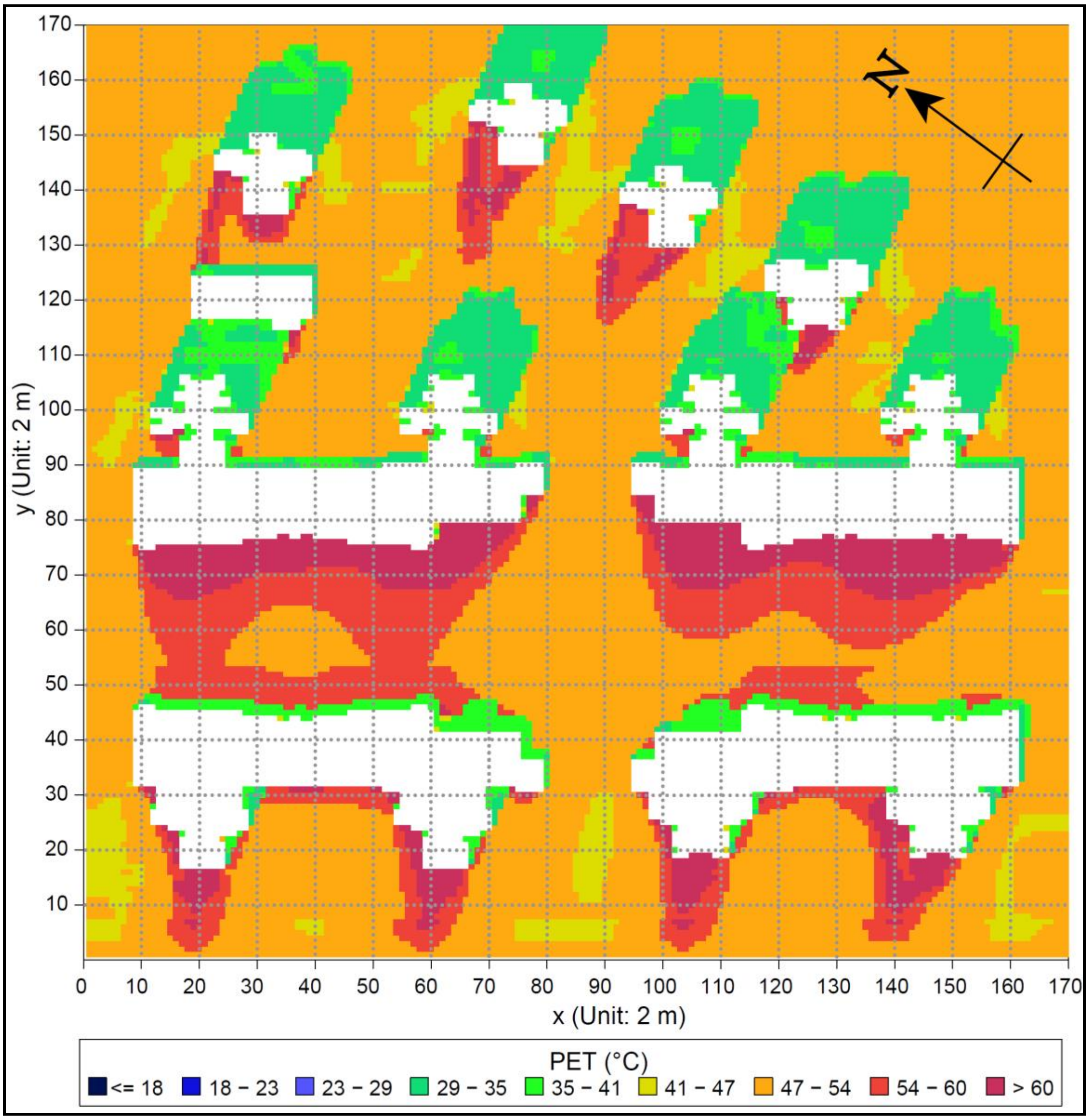

Fig. 5 PET values of the design area (z: 0-3 m) at 14 LST in the simulation day of July

5. Conclusions

In order to provide a comfortable outdoor space, thermal comfort conditions should be taken into account in the design phase of community environment design. Architects also demand a simple and brief approach to assess the thermal comfort conditions, thereby to fulfil the requirement of human thermal comfort. Evaluation of the thermal comfort conditions should contain (1) the long-term data analysis for distinguishing the period with different thermal conditions, and (2) the short-term simulation analysis of the design space in order to locate the undesirable area regarding thermal comfort. Evaluation and visualisation of the thermal comfort could help architects and urban planners to identify these particular areas in the analysis phase of design, thereby modify the thermal conditions evidently and directly.

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References

ASHRAE Handbook, 2001: Fundamentals. *American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.*, Atlanta 111

Bruse M., 2004: ENVI-met 3.0: updated model overview. *University of Bochum Retrieved from: www envi-met com*

Bruse M., Fleer H., 1998: Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software*, **13 (3)**, 373-384

Chen H., Jia B., Lau S., 2008: Sustainable urban form for Chinese compact cities: Challenges of a rapid urbanized economy. *Habitat International*, **32 (1)**, 28-40

Chen H., Ooka R., Harayama K., Kato S., Li X., 2004: Study on outdoor thermal environment of apartment block in Shenzhen, China with coupled simulation of convection, radiation and conduction. *Energy and buildings*, **36 (12)**, 1247-1258

Fanger P. O., 1973: Assessment of man's thermal comfort in practice. *British journal of industrial medicine*, **30 (4)**, 313-324

Fanger P. O., 1970: Thermal comfort. Analysis and applications in environmental engineering. *Copenhagen: Danish Technical Press*.

Gaubatz P., 1999: China's urban transformation: patterns and processes of morphological change in Beijing, Shanghai and Guangzhou. *Urban Studies*, **36 (9)**, 1495-1521

Höppe P., 1999: The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, **43 (2)**, 71-75

Huttner S., Bruse M., Dostal P., 2008: Using ENVI-met to simulate the impact of global warming on the mi-croclimate in central European cities. *In 5th Japanese-German Meeting on Urban Climatology*, 307-312

Lin T. P., 2009: Thermal perception, adaptation and attendance in a public square in hot and humid regions. *Building and environment*, **44 (10)**, 2017-2026

Matzarakis A., Mayer H., 1996: Another kind of environmental stress: thermal stress. *WHO Collaborating Centre for Air Quality Management and Air Pollution Control Newsletters*, **18**, 7-10

Matzarakis A., Mayer H., Iziomon MG., 1999: Applications of a universal thermal index: physiological equivalent temperature. *International Journal of Biometeorology*, **43 (2)**, 76-84

Matzarakis A., Rutz F., Mayer H., 2007: Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *International Journal of Biometeorology*, **51 (4)**, 323-334

Matzarakis A., Rutz F., Mayer H., 2010: Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. *International Journal of Biometeorology*, **54 (2)**, 131-139

Mayer H., Höppe P., 1987: Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, **38 (1)**, 43-49

Oke T. R., 2002: Boundary layer climates. *Routledge*.

Oke T. R., 2006: Towards better scientific communication in urban climate. *Theoretical and Applied Climatology*, **84 (1-3)**,179-190

Streiling S., Matzarakis A., 2003: Influence of single and small clusters of trees on the bioclimate of a city: a case study. *Journal of Arboriculture*, **29 (6)**,309-316

Tang Y. Q., Cui Z. D., Wang J. X., Lu C., Yan X. X., 2008: Model test study of land subsidence caused by high-rise building group in Shanghai. *Bulletin of Engineering Geology and the Environment*, **67 (2)**,173-179

Yang F., Lau S. S., Qian F., 2010: Summertime heat island intensities in three high-rise housing quarters in inner-city Shanghai China: Building layout, density and greenery. *Building and environment*, **45 (1)**,115-134