International Journal of High-Rise Buildings
June 2016, Vol 5, No 2, 87-94

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

High-Rise Urban Form and Environmental Performance - An Overview on Integrated Approaches to Urban Design for a Sustainable High-Rise Urban Future

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Abstract

High-rise as a building typology is gaining popularity in Asian mega-cities, due to its advantages in increasing volumetric density with limited land resources. Numerous factors contribute to the formation of high-rise urban form, from economical and institutional, environmental to socio-political. Environmental concerns over the impact of rapid urbanization in developing economies demand new thought on the link between urban environment and urban form. Outdoor and indoor climate, pedestrian comfort, and building energy consumption are all related to and impacted by urban form and building morphology. There are many studies and practices on designing individual "green" high-rise buildings, but far fewer studies on designing high-rise building *clusters* from the perspective of environmental performance optimization.. This paper focuses on the environmental perspective, and its correlation with the evolution of the high-rise urban form. Previous studies on urban morphology in terms of environmental and energy performance are reviewed. Studies on "parameterizing" urban morphology to estimate its environmental performance are reviewed, and the possible urban design implications of the study are demonstrated in by the author, by way of a microclimate map of the iconic Shanghai Xiao Lujiazui CBD. The study formulates the best-practice design guidelines for creating walkable and comfortable outdoor space in a high-rise urban setting, including proper sizing of street blocks and building footprint, provision of shading, and facilitating urban ventilation.

Keywords: Microclimate, Outdoor thermal comfort, Pedestrian friendly, Environmental sustainability, High rise, Urban morphology

1. Introduction: High-Rise and Environmental Sustainability

Sustainability is undoubtedly one of the most important issues today, but the meaning is often paradoxical and it can be difficult to measure the degree of sustainability due to its all-embracing definition. It is widely accepted that there are three pillars of sustainability, i.e., economic, social and environmental. The interest of this article is on the environmental aspect. Generally, the high-rise building typology is not usually considered environmentally sustainable, due to its intensive use of energy, material and other resources during its whole life cycle, although it has merits, such as saving land resources and transportation costs [1]. When assessing the environmental sustainability of buildings, often a target of "doing less harm" instead of "doing more good" is set, and it certainly applies to high-rise buildings. A number of tall buildings featured with sustainable environmental design can be found in different geographical locations with distinct climates, for example, the Commerzbank in Frankfurt by Foster and Partners, Menara Mesiniaga in Subang Jaya, Malaysia, by Ken Yeang, Deutsche Messe AG in Hannover, Germany, by Thomas Herzog, KfW Westarkade by Sauerbruch Hutton, etc. Invariably they focus on individual tall buildings, rather than a group of buildings. By contrast, the sustainable environmental urban design of high-rise buildings is much less studied. Research at larger scales is an urgent need, as high-rise urban form is changing the skylines of Asian mega-cities, whereas a number of environmental issues (air pollution, urban smog, urban heat islands, etc.) are considered related to high-rise, high-density urban development.

The high-rise housing morphology found in Asian mega-cities can be traced back to the Radiant City advocated by Le Corbusier nearly 100 years ago, which has had profound influences on modern urban planning. In addition to high capital cost of land, the concerns over climate, i.e., striving for more daylight, cooler breeze and less humidity (and fewer mosquitoes…) are probably understated reasons why high-rise living is widely accepted by urban dwellers in Asian cities such as Shanghai, Hong Kong and Singapore, which have warm and humid climates. For instance, increasing urban ventilation is welcomed in these

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Asian cities, and it is supported by scientific research that, given the same density and plot ratio, the high-rise urban housing, compared to the low-rise detached houses, on average a receives significantly higher level of ventilation in both indoor and outdoor spaces [2-3].

2. Urban Form and Energy

Studies on vernacular settlement and habitats reveal the close relationship between form, climate and energy performance. Energy conservation and passive design to harness free energy (solar, wind, daylight) are key issues in evolving historic urban forms. Urban from factors related to energy performance, e.g., **aspect ratio, surface-volume ratio, window-wall ratio** have long been used in studies on urban form and energy. More recent research using advanced image analyzing techniques reveals that the **passive-to-active volume ratio** can be more important than surface-volume ratio when considering energy consumption holistically [4].

A historical study investigates high-rise building and energy consumption from its birth in the US and classifies tall buildings into five chronological generations [5]. It analyzes the impact of building and urban form on heating, cooling and lighting energy consumption. It is highlighted that the landmark **Zoning Law** that was instated in 1916 reformed the urban geometry, resulting in taller, more slender and set-back, "wedding-cake" towers (Fig. 1). This form improves daylighting conditions for both indoor and outdoor spaces, but building surface-to-volume ratio is increased, and consequently heating energy consumption increased. Therefore, in assessing the environmental performance of the high-rise urban form, aspects related to energy, comfort, daylight and climate should be considered holistically.

3. High-Rise Urban Form and Climate-Responsive Design

Variation of high-rise urban form exists to accommodate various needs of climate moderation. High-rise clusters in cold climates, for instance, generally contain buildings with homogeneous height within a neighborhood, or restrict drastic changes in height between adjacent buildings. The purpose is to create more *skimming flow* over the urban canopy layer (UCL) and thus less downward cold air into the pedestrian level [6]. Therefore, for cities in cold or temperate climates, it was proposed that, for the purpose of wind protection, *"…building height would rise less abruptly. In general, building heights would increase gradually…towards the city center. Building heights in downtown areas would be set similar to the contour lines of a hill, with the highest structures permitted in the center. Wherever height zones are abutted, the change in height allowed would be less than half of that allowed in the adjacent higher height zone"* [7]. The resultant urban-center skyline could be found, for instance, in downtown San Francisco [8]. In cold climates, the geometry of tall buildings flanking streets would generally favor multi-story buildings, with recessed podiums and large canopies over the main building entrance, to prevent downward airflow from reaching the primary pedestrian area [9]. Tall building clusters in hot climates, on the contrary, should encourage wind channeling and turbulence. Building foot-

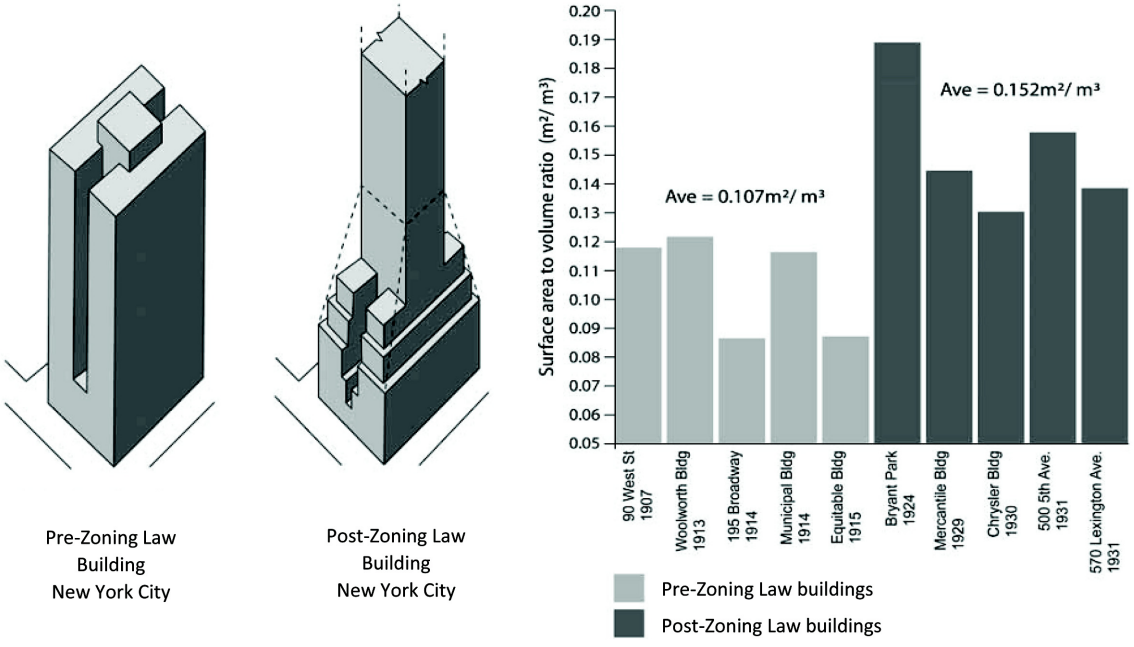


Figure 1. The impact on tall building form and surface-volume ratio [5].

prints should be reduced to generate tall and slim shapes (called "pencil buildings" in some Asian cities) for better outdoor and indoor ventilation. Building height should be varied in a random manner to generate more turbulence and downward airflow into deep urban canyons. For cities in monsoon climates with opposite winter and summer prevailing wind directions, building clusters can be organized by gradually lowering allowable building heights towards the summertime prevailing wind direction [10, 11]. Towers without protruding podiums can introduce more airflow from above down to the pedestrian area, and recessed entrances and portico façades can be ventilation-friendly features for pedestrians [10].

4. Regulations Regarding Urban Form and Environmental Performance

High-rise morphology, if improperly manipulated, can negatively impact the urban environment, particularly at the lower floors and pedestrian levels. In order to alleviate potential environmental hazards related to high-rise development, regulations and by-laws are researched, proposed and reinforced in some Asian countries and cities. For instance, Hong Kong has a typical high-rise high-density urban setting. Located near the tropic of Cancer and within a hot-humid climate, the urban area has long suffered from stagnant air, which leads to a stuffy and uncomfortable pedestrian environment. This can have serious comfort and health impacts on local people. After the outbreak of SARS in 2003, the Hong Kong government initiated a study to explore scientific approaches to evaluating the ventilation impact of new or existing urban developments on local pedestrian areas. The study resulted in the establishment of the Air Ventilation System (AVA). It is a **performance-based**, government led and voluntary system, using **velocity ratio (VRw)** as the indicator and wind tunnels as the measurement platform (Fig. 2). Generally, given the climate of Hong Kong, the principle is "more wind the better". Guidelines of urban ventilation were developed based on the recommendation of this study, and were incorporated in HKPSG urban design guidelines (Chapter 11) [12].

High-rise residential building development in Asian cities is often carried out at the urban neighborhood scale, comprising a group of individual apartment towers. Some **prescriptive** design guidelines have been issued to improve site ventilation. These guidelines are normally formulated based on rigorous scientific research and can be readily applied to design scheme assessment. For instance, large-scale coastal residential developments in Hong Kong used to adopt long linear layouts to maximize the sea or mountain view. This, however, created a walling effect which prevented sea breezes from entering the inner unban area. To deal with this potential environmental hazard, the Building Department of HKSAR reinforced the Sustainable building design guidelines of Hong Kong in 2008 [14]. An indicator called the **Porosity ratio** is manipulated to regulate the permeability (P) of buildings. Simply speaking, it stipulates ratios of areas of intervening and permeable elements at various height levels, as compared to the whole projected area of the assessment zone. In the Chinese Design Standard for Thermal Environment of Urban Residential Areas (JGJ286-2013) issued in 2013 [15], an index called **Frontal area ratio** (FAR) was introduced. The FAR is defined as the ratio of the frontal area of a building facing the dominant wind direction in rela-

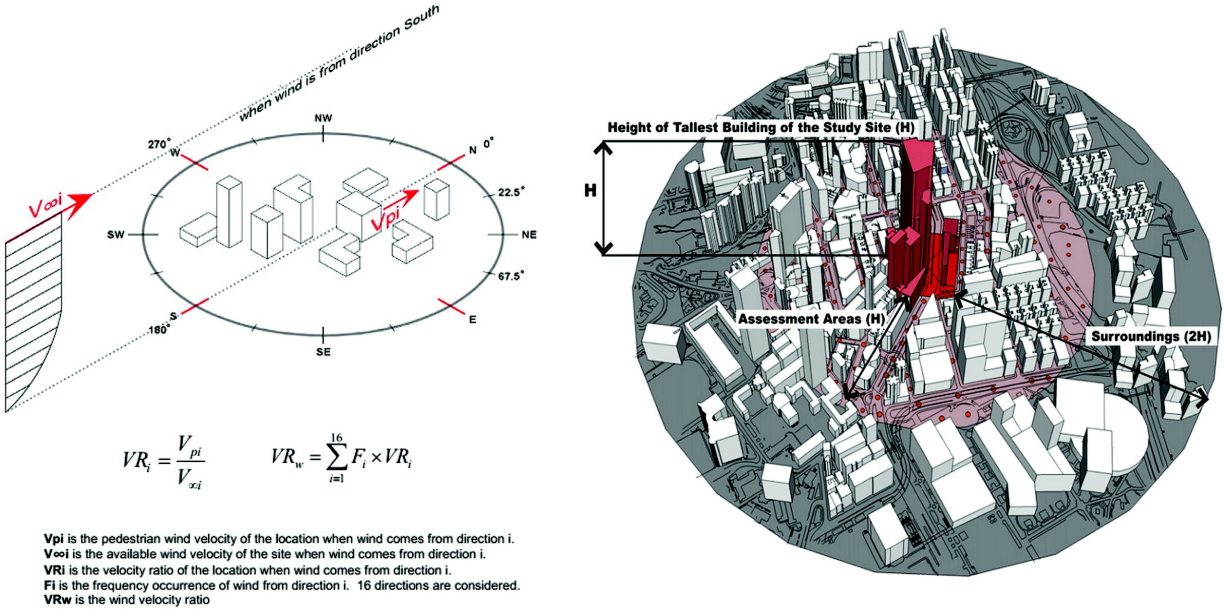


Figure 2. Schematic diagram of wind velocity ratio (VRw) [13].

tion to its largest possible frontal area. The ratio relates the building geometry and orientation with the seasonal prevailing wind direction. New residential developments should comply with the requirements of the summer frontal area ratio based on their respective climate zones. For instance, for the hot-summer and cold-winter (HSCW) zone, site-average frontal area ratio should be lower than 70% [15]. This is particularly important for the linear housing form, so that major façades should be at a certain angle to the prevailing winds, to facilitate site ventilation without compromising building ventilation. The index is very useful for building footprints of a square or circular shape.

5. Mapping Microclimate in High-Rise Urban Form

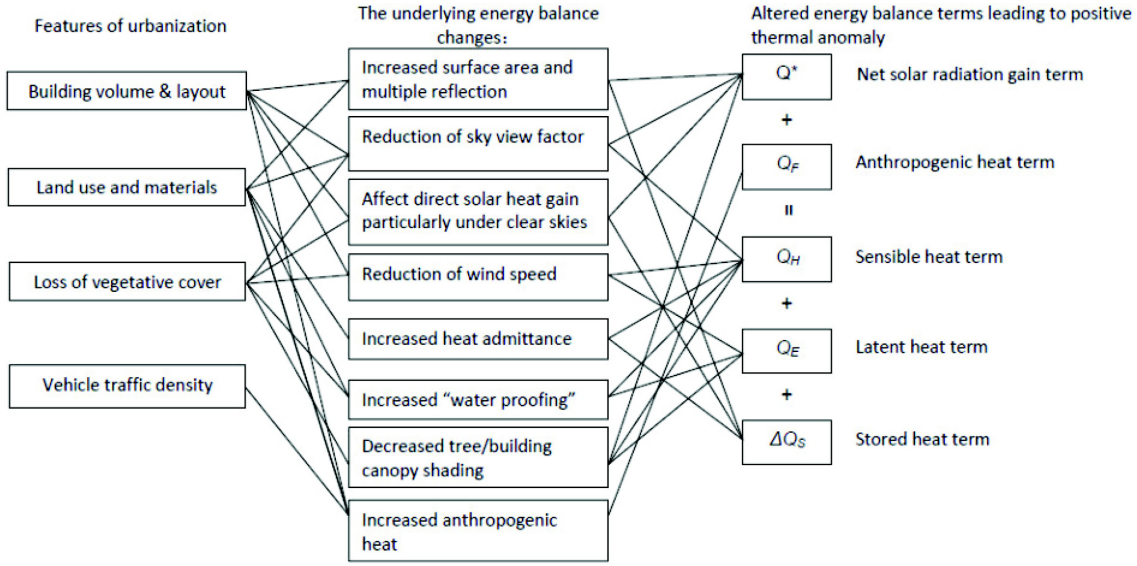
Since the Modern Architecture movement, contemporary urban planning normally adopts a top-down approach, but historically, cities mainly grow from the bottom up, demonstrating the complex interaction among economic, political, cultural and geographical/climatic forces. Scientific approaches, such as network science and fractal geometry, have been developed to explore the complex interaction of these forces and the growth of the urban form, so as to better understand urban density, sprawl, compactness and related sustainability [16]. Similarly, a new methodology is needed to better understand the relationship between urban form and urban climate. This is because contemporary urban growth has been occurring at unprecedented rates due to rapid urbanization, and the ever-increasing height, compactness and density can result in very complex microclimates and thermal environments. It is necessary to understand this relationship and further develop measures to control and improve the microclimate.

Urban designers work on the scale of neighborhoods to urban districts, comprising tens or even hundreds of buildings. The urban climate at this scale (10^{-2}~10^{3} m [6]), can be referred to as a "microclimate," and it could be manipulated by design interventions: building form, height and spacing, pavement and façade materials, street parks and trees, etc. [17]. As mentioned in the previous section, there are plenty of "rules of thumb" of urban building design in response to various kinds of urban climate. Nowadays, as cities keep growing larger and denser, designers are constantly faced with the challenges of working in high-density and high-heterogeneity urban environments. As such, there is a great need for tools to help designers gain a better microclimatic understanding by providing predictive results for different design scenarios with acceptable accuracy and validity. At the more advanced or complex levels, it is necessary to quantitatively evaluate the environmental performance of high-rise urban form to meet certain criteria, e.g., LEED ND compliance. Today the commonly employed tools are based on computational fluid dynamics (CFD) [18]. CFD tools require expertise to operate, are generally resource-costly, and thus unfamiliar and not user-friendly to architects and urban designers.

On the other hand, at the urban scale, urban climatic mapping (UC-Map) is a design decision-supporting tool that aims to provide urban planners with both analytical and visual information [19]. Over the last decade it has received increasing attention from both the research and practice fields. Studies have been carried out in a number of cities in Europe, North America and Asia. On the metropolitan and urban scale, the urban form-based variables are generally categorized into two layers: Thermal Load and Dynamic Potential; regional wind information was also provided [20]. The established framework has been applied in various cities in Germany, and has influenced the paradigms used in subsequent UC-Map studies and applications across the world [21,22].

Earlier UC-Maps generally stratify climate information based on land use, and rely largely on expert evaluation. A more recent UC-Map in Hong Kong factors building density, topography, ground roughness and greenery into street-level urban microclimate evaluation [23]. Additionally, a moresystematic and quantitative approach is taken, using the two key urban morphological variables, sky view factor (SVF) and frontal area density (FAD), to describe thermal and aerodynamic characteristics of the high-density Hong Kong urban environment. Aided with digital image analysis techniques and GIS systems, the morphological factors are mapped onto virtual city spaces and overlaid based on expert estimates to generate microclimate thermal comfort maps [24]. The authors further developed this approach by incorporating empirical models built upon carefully-selected urban morphological variables [25,26] (Fig. 3). This empirical modeling method can be supplementary to the state-of-the-art UC-Map systems. The derived thermal atlas system is suitable for Shanghai's unique urban characteristics and climatic conditions, and is easy to use in urban design practice.

The Shanghai Lujiazui Central Business District was selected as a test bed for the method. Shanghai (30°40'N ~31°53'N, 120°51'E~122°12'E), the biggest city in China, is located on the alluvial terrace of the Yangtze River delta, with average elevation of 4 m above sea level. It has a northern subtropical monsoon climate, with a mean annual temperature of 17.2°C, and monthly mean maximum temperature of 30.2°C in July and monthly mean minimum temperature of 1.9°C in January, respectively [27]. The Lujiazui Central Business District is located in the Pudong New District on the eastern bank of Huangpu River, across from the Bund. The total land area is 1.7 km^2, and covers commerce, business and high-end residential land uses. The total building floor area is about 4.35×10^6 m^2, and the gross floor area ratio is about 2.5 (Fig. 4). With more than 40 high-rise buildings >200 m, Lujiazui CBD is considered one of the most important financial hubs in China, and its planning and design has had strong influence on the development practice of other Chinese



Figrue 3. Interconnection among urbanization, morphology and urban energy balance (after [6]).

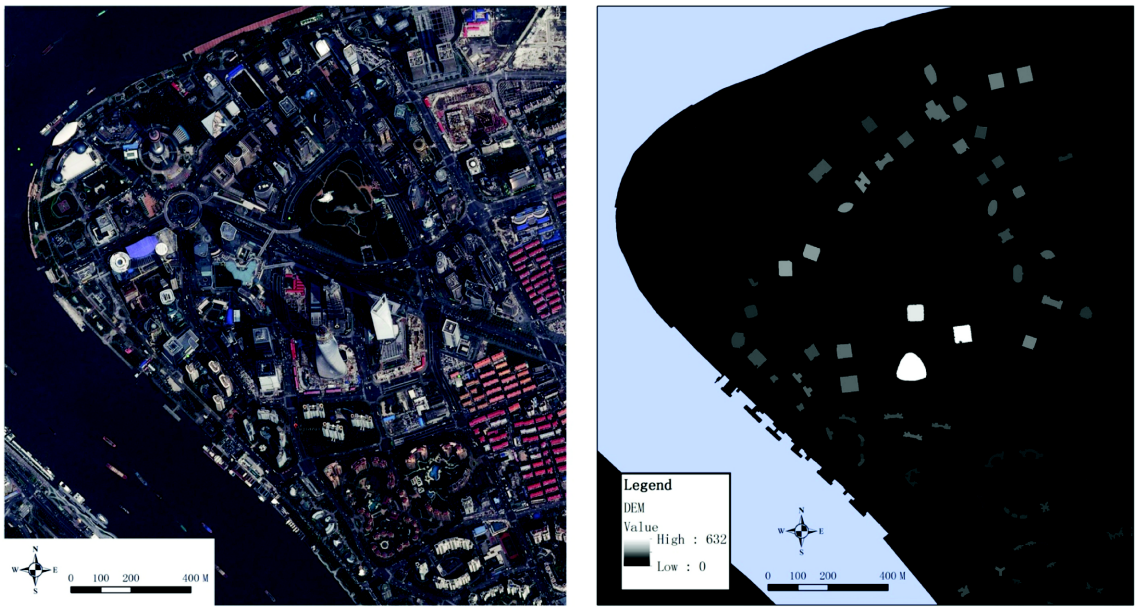


Figure 4. (a) Map of Lujiazui CBD in Shanghai (b) DEM.

cities.

Six key morphological indicators, i.e., sky view factor, pavement cover ratio, vehicle traffic density, green plot ratio, frontal area index, and proximity to heat sink (refer to ref. [28] for details of these parameters) were used to describe different aspects of the urban thermal environment including building density, land use, anthropogenic heat, greenery, ventilation potential, and heat sink. Spatial analysis tools were developed in GIS to generate maps for these morphological indicators using the digital elevation model (DEM). In-situ meteorological measurements were carried out on peak summer days to investigate the spatial variation of microclimatic parameters, based on which the physiological equivalent temperature (PET) index was calculated. Empirical regression models were built, correlating PET values with local morphological indicators, from which PET maps were generated. This thermal atlas system can rapidly analyze and visualize the spatial variations of urban microclimate from the thermal comfort aspects as affected by different urban design sce-

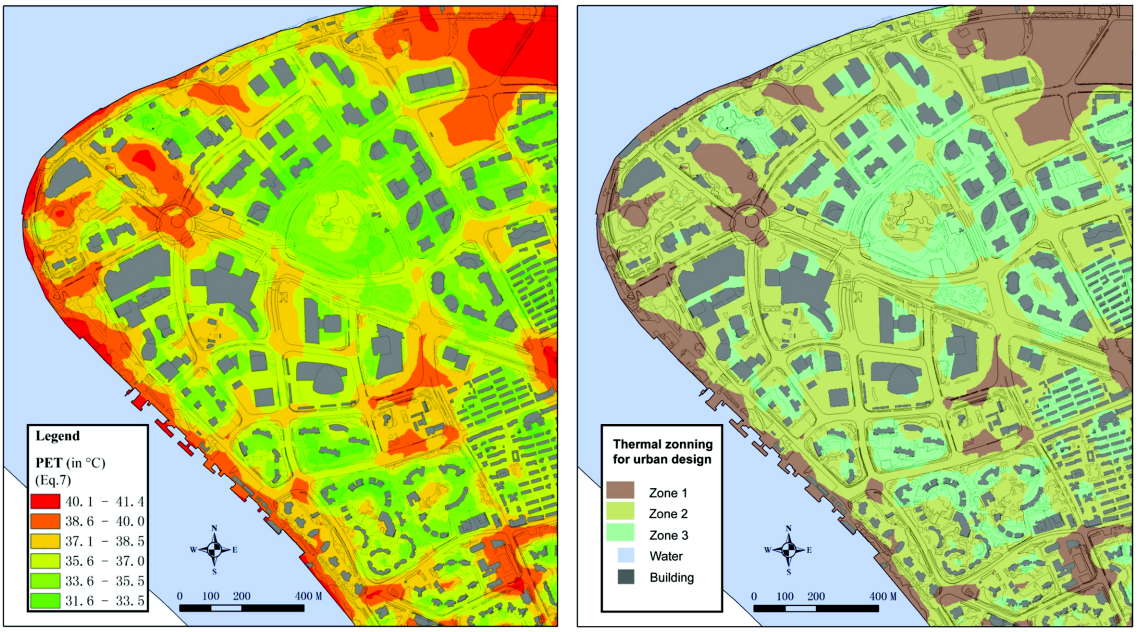


Figure 5. Summer daytime thermal atlas of Shanghai Lujiazui CBD (index: PET) and Thermal zoning map based on PET map.

narios. Thus, it can be a useful decision-support tool for urban design meant to alleviate urban heat island intensity and improve outdoor thermal comfort [28].

Based on the thermal zoning map (Fig. 5), proposals are made to improve summertime microclimate and thermal comfort, including: 1) providing opaque shading devices for major pedestrian spaces along the Century Walkway and Waterfront Esplanade. 2) Reducing the size of street blocks, and dividing massive single buildings into building clusters with smaller spacing. Denser urban fabric creates shaded outdoor spaces between buildings, whereas isolated tall or large buildings generally occupy larger street blocks, and are separated by wide roads. This leads to an uncomfortable pedestrian environment, because of lessened solar protection, and more sensible heat from nearby road pavement materials. Refining the urban grid and building fabric a block size of 150~250 m on each side not only improves daytime thermal comfort, but also makes the city more pedestrian-friendly. 3) Improving the accessibility to the prominent heat sinks. For instance, expanding the existing walkway system to improve the connection between surrounding office buildings with Lujiazui Central Green, so as to increase the occupation and usage of LCG during lunch hours and weekend days; designing building and landscape elements carefully, for instance, by reorganizing short walls, trees etc., so as to introduce more cool breeze from LCG to its surrounding built-up areas.

6. Concluding Remark

Today, the mainstream of sustainable design requires energy-efficient and carbon-neutral design to combat resource depletion and global warming. Tall buildings face lots of challenges because they are considered to consume more materials and energy during the whole life cycle process. To make the tall building "greener", the design of tall buildings is undergoing a paradigm shift. For instance, designers are nowexploring form and façade design to harness renewable energy and resources (solar, wind, rain, greenery, etc.), which can be witnessed by the projects mentioned in the first section of this article. Compared with individual buildings, the environmental performance of tall building clusters at the neighborhood and district levels are under-investigated.

Based on concepts developed in systems ecology, Braham explores environmental building design at three nested scales, i.e., shelter, setting and site. Environmentally sound buildings and cities should act as resilient self-organized ecosystems [29]. From the environmental point of view, tall buildings should not be considered stand-alone objects, but a part of larger web of interwoven ecological systems. As reviewed in this article, there are increasing numbers of studies on the ecological and environmental performance of the high-rise urban form from various aspects. As the trend of building tall will likely continue in urban areas, particularly in large Asian cities, the studies at neighborhood and district scales are highly necessary. As evidenced in the Shanghai Lujiazui study, a top-down urban design approach that delivers only an iconic "postcard" urban image can have many negative consequences, one of which is a deteriorated outdoor microclimate that is not supportive of sustainable urban

spaces. Environmentally, a high-rise city is a high-risk and a high-potential at the same time. To maximize the potential and minimize the risk, more inter-disciplinary and cross-disciplinary research is needed now, and in the near future.

Acknowledgements

The paper is supported by the China National Natural Science Funds (Project No.: 51378354), the Innovation Program of Shanghai Municipal Education Commission (Project No.: 15ZZ020), and the Fundamental Research Funds for the Central Universities (Project No.: 0100219 161).

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