Simulation of the Urban Space Thermal Environment

Subjects: Environmental Sciences

Contributor: Hongyuan HUO

The urban space thermal environment (USTE) is spatially expressed as the horizontal and vertical distributions of the surface temperature and atmospheric temperature fields. With the urban space temperature field as the core, the USTE is the physical environmental system in which the underlying surface, atmospheric transmission and solar radiation are influenced by humans and their interactions with nature. The urban thermal environment has significant impacts on the urban climate and micrometeorology; it is an important indicator used to measure the state of the urban ecological environment, and its temporal and spatial evolution processes are closely related to societal and economic activities.

computational fluid dynamics urban space thermal environment urban heat island

urban landscape remote sensing

1. Introduction

In recent years, with the acceleration of urbanization and the rapid development of industry, populations have been migrating to cities [1], resulting in various urban ecological and environmental problems [2]. Among them, the urban thermal environment has become particularly prominent, attracting widespread attention from many scientists [3][4]. Urban thermal environment issues affect people’s living comfort, the urban climate, the atmospheric environment, and biological habits, often lead to enhanced energy consumption and greenhouse gas emissions, and increase the incidence and mortality of thermal environment-related diseases [5].

The urban space thermal environment (USTE) is spatially expressed as the horizontal and vertical distributions of the surface temperature and atmospheric temperature fields [6]. With the urban space temperature field as the core, the USTE is the physical environmental system in which the underlying surface, atmospheric transmission and solar radiation are influenced by humans and their interactions with nature [7][8][9][10]. The urban thermal environment has significant impacts on the urban climate and micrometeorology; it is an important indicator used to measure the state of the urban ecological environment, and its temporal and spatial evolution processes are closely related to societal and economic activities [11][12]. Therefore, studying the USTE and spatially quantitatively analyzing the distribution of the urban spatial temperature field, considering the effects of temporally and spatially varying processes, is of great importance to urban ecological security and sustainable development.

The current methods for quantitatively studying three-dimensional USTEs include ground observation, remote sensing, and numerical simulation [13]. USTE research based on ground observations has provided effective estimates of the distribution and spatiotemporal dynamics of station temperatures at different time scales, but the spatial representation of these discretely distributed weather stations is poor. Although USTE research based on remote sensing can retrieve the surface temperature field and the surface ecological parameters, the heat transfer among different underlying surfaces is not considered. Numerical simulation can be used for the three-dimensional simulation of USTEs [5][14]. Computational fluid dynamics (CFD) is one of the most commonly used numerical simulation methods and can be used to simulate the motion of turbulent fluids. Combining the advantages of fluid mechanics and heat transfer, CFD can simulate the physical processes of heat conduction and heat convection among underlying surfaces in a city at a fine scale [15].

However, few studies have summarized the current status of research on the urban thermal environment based on CFD methods or the integration of CFD and remote sensing. Therefore, a timely review of research on CFD simulations of the USTE is valuable for further understanding the mechanisms of the USTE, improving urban planning and design, mitigating negative changes to the urban thermal environment, and quantitatively evaluating the urban thermal environment and human comfort levels. Thus, we summarize the current research status of CFD-based urban thermal environment problems over the past two decades, the related methods of USTE monitoring based on CFD models, the influential factors and corresponding relationship between CFD and the USTE, and the progress achieved with USTE mitigation measures. Future research directions and research focuses based on CFD methods are proposed.

2. Quantitative Simulations of the USTE Based on CFD Considering the Underlying Surface Dynamics

The high-temperature thermal environment in urban areas is a negative effect produced by the process of urbanization. The corresponding formation mechanism is complex and significantly regional. The main factors that influence the USTE include changes in the natural attributes of the underlying surface of the city, anthropogenic heat emissions, and air pollution. In particular, the changes in the urban underlying surface are important contributors to the urban heat island effect [6][16]. The changes in the underlying surface of a city mainly include changes in land use/land cover (LULC), the structure of the underlying surface, and the spatial geometric topological relationships among different underlying surface components [17][18]. The rapid development of urbanization has resulted in a large number of natural surfaces being replaced by urban impervious surfaces, which are the main contributors to the urban thermal environment; moreover, reductions in vegetation and water bodies, which play important roles in mitigating negatives changes in the urban thermal environment, have occurred [19].

2.1. Relationship between Changes in LULC and the USTE

The rapid development of urbanization has led to dramatic changes in LULC. The conversion of cultivated land, bare soil, and other natural land types into urban residential areas, industrial areas and commercial business districts has resulted in the replacement of the natural surfaces of cities with impervious surfaces. As a result, the physical properties of the underlying surface, such as the albedo, emissivity, thermal inertia, specific emissivity and thermal conductivity, have significantly changed [20][21]. These changes have led to a decline in the self-moderating ability of the urban thermal environment.

Changes in urban LULC have significantly affected the heat exchange between the surface and the atmosphere [22][23]. Research on the relationship between surface radiation and the energy balance based on CFD simulation has also attracted widespread attention from scholars [24]. Takahashi et al. (2004) used CFD numerical simulation methods to simulate the changes in the energy flux among soil, vegetation, the atmosphere and buildings and the heat exchange among various influential factors. The simulation results showed that when large numbers of green areas and water bodies are converted to urban land, the surface temperature will increase, resulting in direct changes to the USTE [25].

2.2. Relationship between the Underlying Surface Structure and the USTE

The changes in the underlying surface structure mainly include changes in urban vegetation coverage, water coverage, and building area caused by replacing natural permeable surfaces with urban impervious surfaces (often made of cement, asphalt, concrete and other building materials). This process will result in a positive effect for the USTE in the following two aspects. On the one hand, impervious surfaces have a stronger ability to absorb solar radiation than do natural surfaces. In addition, in the urban canopy space, part of the solar radiation reflected from the ground is absorbed in the process of reflection between buildings, which is the main energy source of the USTE [26]. On the other hand, the density of buildings in metropolitan areas is high, the number of high-rise buildings is large, and the surface roughness is high, resulting in poor urban ventilation, which causes heat to accumulate over a short period of time. If the heat cannot be appropriately discharged, the urban temperature will continue to rise and remain at a high level, thereby increasing the intensity of the USTE.

Reasonable underlying surface types and layout structures are important factors that need to be considered to alleviate the USTE [27]. Dimoudi et al. (2014) changed the roads and streets in a model from cement mixed with clay to cold materials, used CFD to simulate the temperature field distribution, and found that the surface temperature dropped by 6.5 °C [28]. According to the results of CFD simulations of wind and heat environments, Fatima et al. (2017) found that hot spots in high-temperature areas in cities have a certain correlation with low wind speeds [29]. Undeveloped areas, such as natural soil, grassland, woodland, and cultivated land areas that have been artificially developed, are characterized by good water permeability and can convert absorbed solar radiation energy into latent heat energy, which can effectively mitigate the rate of increase in surface temperature. Radhi et al. (2015) analyzed the distributions of, and differences in, the wind and heat environments between natural islands and human-made islands based on CFD simulations. Compared to uninhabited natural islands, artificial islands are mostly composed of various buildings and roads with impervious underlying surfaces, which are characterized by poor water permeability and air permeability and become hot faster than other surfaces. Under the same thermal environment requirements, the cooling capacity of human-made islands has increased by 14–26% [22]. Therefore, the proportion and layout of different underlying surfaces should be reasonably established in the relevant design and construction stages to optimize the urban wind and heat environments.

2.3. Relationship between the USTE and Urban Green Spaces and Waterbodies

A change in the underlying surface of a city can change the distribution of latent heat and sensible heat, potentially leading to the formation urban heat island effects [30]. Many scientists have explored the relationship between different land use types and heat island effects by integrating CFD and RS/GIS technologies [31]. Studies have shown that the types of land used for urban construction and transportation are significantly positively correlated with the urban heat island effect, and cultivated land, forest land, water bodies and other land use types are significantly negatively correlated with the urban heat island effect [32][33]. In the case of the same green area, for every 1% increase in the impervious surface area surrounding a green area, the cooling range of the green area will decrease by approximately 4.01 m [34]. Lin et al. (2007) used the regional atmosphere simulation system MM5 to simulate the urban heat island effect in Beijing; their results showed that water bodies and green spaces have a good control effect on the temperature near the ground [35]. Huang et al. (2020) simulated the wind and heat environments in Taiwan through a CFD model. They obtained quantitative indicators to improve the thermal environment and found that the green area ratio should be at least 60% to significantly improve the thermal effect [36]. Therefore, the type of urban green space, vegetation coverage, and spatial layout can all affect the urban thermal environment [37][38].

The area percentages of green space and different vegetation types affect the distribution of the thermal environment. Therefore, the quantitative impact of urban green plants on the USTE has become a hotspot in CFD-based thermal environment research in recent years. Zhang et al. (2017) found that the spatial cooling effect of a green belt becomes weaker as the area decreases [39]. When the proportion of green space reaches 20–35%, the cooling effect will be significantly enhanced, and as the green space proportion increases, the thermal comfort index will increase [40]. However, the cooling distance range of a green space generally stays between 150 m and 250 m [34]. Liu et al. (2012) simulated the impact of different vegetation types on the urban wind and heat environments based on CFD and found that shrubs hinder the flow field more-so than do trees. Because shrubs have a stronger impact on wind speed than trees, it is not advisable to position too many shrubs upwind of areas that require ventilation [41].

Under the same area conditions, various green space morphological characteristics have different effects on the thermal environment. In terms of mitigating the effects of the thermal environment, wedge-shaped and radially distributed green spaces have the best cooling effect [41]. The cooling effect of strip-shaped areas is relatively poor, but if the distribution can be well matched with ventilation corridors, these areas can also produce an excellent cooling effect [42]. A dotted green space pattern can break up high-temperature urban heat island areas and has displayed advantages in improving the thermal environment and microclimate in local areas of a city [40]. In the case of the same green area, the cooling range of the green area decreases as the shape index increases and as the perimeter of the green area increases [34].

3. Anthropogenic Heat Emissions and the USTE

During the rapid process of urbanization, the heat generated by human production and activities, including the heat generated by transportation, energy consumption and industrial production and the heat released by the electrical appliances used in daily life [43], has enhanced the urban thermal environment and significantly impacted the local urban climate [44]. Most urban heat island centers are located in populated residential areas, industrial areas, and urban central business districts, and the intensity of heat islands is greatly affected by human activities, making it difficult to estimate anthropogenic heat.

In the field of urban microclimate research, there are three main methods used to calculate anthropogenic heat [45], including the source inventory method, the energy balance equation method, and the numerical model simulation method. Fan et al. (2005) used the PBL model in the MM5 climate simulation package to study the thermal environment in Philadelphia and found that anthropogenic heat has a significant impact on the urban heat island effect, especially at night and in winter [46]. To introduce anthropogenic heat emissions into the CFD numerical simulation process, He et al. (2007) added anthropogenic heat to the surface energy balance equation and atmospheric heat conservation equation in a certain proportion based on a multiscale model; then, the urban thermal environment in Nanjing, Jiangsu Province, eastern China, was simulated based on the multiscale model system. They found that the contribution of anthropogenic heat source emissions to the urban heat island reached 29.6% [47]. Qian et al. (2020) generated a gridded anthropogenic heat flux benchmark dataset with a spatial resolution of 1 km based on machine learning; they found that the anthropogenic heat emissions in the city center were 60–190 W/m^2, and the largest value of anthropogenic heat emissions in the industrial zone was 415 W/m^2 [48]. These research results show that anthropogenic heat has become a major component of urban thermal environment research.

At present, most studies on USTEs based on CFD simulations at the block scale or macroscale do not consider the influence of anthropogenic heat emissions, which is a possible reason for the low simulation accuracy of these CFD models. However, at the microscale, a few scholars have performed research on indoor human thermal comfort considering the heat generated by the human body.

Recently, few studies have considered the influence of anthropogenic heat emissions when using CFD methods to simulate the USTE. Determining how to quantify anthropogenic heat emissions and couple them with thermal environment simulation models based on CFD is important for accurately simulating the USTE; this topic should be addressed in future research in this field. Therefore, at the block scale and macroscale, anthropogenic heat includes not only the heat emitted by humans but also the heat generated by human activities, such as transportation and industrial production. However, the estimation of anthropogenic heat is complicated. Coupling anthropogenic heat emission predictions with CFD simulation models is one of the challenges faced in the current research on CFD-based USTE simulations.

4. Research on Mitigation Measures for USTEs Based on CFD Simulations

The urban thermal environment is influenced by the wind environment, solar radiation, anthropogenic heat, geographic and topographic features, underlying surface thermal properties, heat conduction and thermal radiation among components of the underlying surface, and atmospheric heat convection at different altitudes [49]. To quantify and mitigate negative effects on the USTE, many scientists have performed studies on cooling cities and increasing ventilation in urban areas. Lai et al. (2019) summarized and described the cooling effects on the urban thermal environment and mechanisms of the four main mitigation strategies of changing the urban geometry, increasing vegetation, permeable surface and water bodies [50]. The influencers and mechanisms of the USTE have been analyzed from multiple dimensions and perspectives, and corresponding methods and measures have been proposed to control the USTE according to the characteristics of different cities. These measures mainly include the planning and layout of green plants and water bodies, the rational planning of building complexes, the reasonable layout and optimization of urban ventilation corridors, and the use of green and energy-saving building materials (as shown in **Table 1**).

Table 1. Research on control methods for the urban thermal environment based on CFD.

Mitigation Measures	Focus	Typical Reference
Waterbodies	Water area and proportion	Tominaga 2015
	Water morphological characteristics	Montazeri 2017
Vegetation and green spaces	Vegetation type	Gülten 2016; Dimitris 2017; Gromke 2015
	Vegetation form and layout	Liu 2012; Li 2016; Du 2019; Vuckovic 2018; Zhou 2016; Lin 2019
	Green area and proportion	Wang 2019; Huang 2020; Liu 2019
Building layout and materials	Building layout	Schrijvers 2020; Peng 2017; Liu 2020; Allegrini 2017
	Building materials	Maragkogiannis 2014; Dimitris 2017; Gagliano 2017; Ferrari 2020; Santamouris 2018; Allegrini 2017; Dimoudi 2014; Priyadarsini 2008
	Planning of the underlying surface	Chen 2018; Li 2008; Hsieh 2016; Kubilay 2019; Yi 2018; Zhou 2018
Planning and design of ventilation corridors	Planning and design of urban ventilation corridors	Ashie 2011; Hsieh 2016; Wu 2009; Tominaga 2008; Antoniou 2017; Allegrini 2014

4.1. Water Bodies for Controlling Heat in the USTE

Water bodies have a large specific heat capacity, and the rate of temperature increase is slower for water than for buildings and other surface components in cities. Under the actions of evaporation and transpiration, a water body exchanges heat with the atmosphere close to the water surface by absorbing heat and converting solar radiant energy into latent heat. Under the influence of the wind field, the cold air in the upper layer of the water body exchanges heat with the surrounding airflow, making the temperature around the water body much lower than that in areas with buildings [51].

As a heat sink, the cooling effect of a water body is related to its area, shape, and distance from a target. Yang et al. (2015) used a CFD model to simulate a river and the wind-heat environment under different building layouts. They found that when the angle between a building and a river is in the range of 45–90°, the outdoor thermal environment effect is minimal. In terms of the building height layout, a layout from low to high is better than a layout with a constant height [52]. Du et al. (2019) used a CFD model to simulate the influence of water bodies with different morphological characteristics on the heat island effect [42]. The results showed that a water body with a complicated outer contour provides a better cooling effect than a water body with a uniform outer contour. Notably, the outer surface of a complex contour is larger, which enables the water body and the air to fully exchange heat. The cooling effect that a water body can provide is also affected by the distance to the target. The closer the target is to the water body, the better the cooling effect. When a building is far from a water body, the cooling effect is weakened. Ashie et al. (2009) found that the area within a range of 100–200 m on both sides of a river is obviously affected by the cold wind that blows across the river; in contrast, the temperature in inland areas was higher [53].

The efficiency with which water bodies mitigate the effects of the USTE is affected by the combined effects of wind speed, wind direction, external shape, spatial location and area. Tominaga et al. (2015) simulated the cooling effect of water on the thermal environment of buildings based on CFD simulations. The results showed that the maximum cooling effect at pedestrian height can reach 2 °C, and the average cooling effect is approximately 0.5–1 °C. With a wind speed of approximately 3 m/s at a height of 10 m, the cooling effect caused by evaporation spreads more than 100 m downwind [54]. Hsieh et al. (2016) conducted a CFD simulation study of the ventilation environment in Shanghai and found that in urban planning, placing a water body upwind in the dominant wind direction can effectively alleviate the local heating effect [55]. Song et al. (2011) proposed a new calculation method for heat transfer and moisture transfer between water bodies and the atmosphere to study the impact of urban water bodies on the humidity and thermal environments of surrounding buildings [56].

From the current literature, the quantitative relationship between the shape of a water body and the cooling range under different wind speeds has not been clarified. In addition, the high-humidity environment formed by the evaporation of water will also affect the comfort of humans. Therefore, the quantitative relationship between these factors and comfort evaluations are important research topics related to the effects of water bodies on the urban thermal environment. When considering the mitigation of the thermal environment by a water body, the relationships among the water body, the wind speed and direction, and the building layout should be considered to control the spatial thermal field.

4.2. Green Space and Vegetation for Controlling the USTE

The central role of green space and vegetation in mitigating the heat island effect has attracted widespread attention from scholars [57]. The recent research has focused on the mechanism and influence of green plants in the urban thermal environment [58][59][60], the simplification of the vegetation model and its coupling with CFD [57][61], and the relationship between the USTE and various vegetation parameters, such as the relationships between the intensity of urban heat islands and vegetation index values [62][63], vegetation abundance [64], and the standardized compactness index [39].

The mechanism by which green vegetation mitigates the heat island effect is mainly reflected by the following two factors [60]. On the one hand, vegetation absorbs part of the solar radiation for photosynthesis and reflects part of the solar radiation from its leaves [28]. The temperature difference caused by trees by blocking solar radiation and absorbing energy can reach 6 °C [65]. On the other hand, the transpiration of vegetation absorbs most available heat and creates a latent heat flux, which slows the increase in temperature. Under the combined effect of tree transpiration and shading, the outdoor thermal comfort index can be effectively improved [66]. In addition, the cooling effect of green land vegetation is based on different principles at different heights. At a height of 2 m, cooling is achieved by shielding solar radiation and exchanging latent heat. At a height of 10 m, cooling is achieved by heat exchange between vegetation and the atmosphere [67].

Increasing the vegetated area and optimizing the green space structure and layout are two important measures to mitigate the USTE. Enlarging the area of an urban green space is an effective way to mitigate the urban heat island effect. The change in the leaf area index has a significant impact on the thermal comfort of the human body. The increase in the greening rate will lead to a decrease in the air temperature and the physiological equivalent temperature [68][69][70]. Lin et al. (2020) noted that for every 10% expansion in street vegetation coverage, the air temperature at the pedestrian level (height) will drop by 0.15 °C [71]. However, when the built-up area or urban land area is limited, it is not economical to rely on increasing the green area to alleviate the thermal environment problem. The most important task is rationally optimizing the structure and pattern of the green area in a limited region to achieve maximum utility. Du et al. (2019) found through CFD simulation that the layout of green vegetation with complex shapes has the best cooling effect in alleviating the effects of the thermal environment [42].

When seeking to control the thermal environment based mainly on vegetation in specific areas, various factors, including the proportion of green area, the type and spatial layout of greenery, the coordination and layout of green buildings and the wind field, must be comprehensively considered to achieve the best mitigation efficiency. To reduce the USTE, most research shows that an increase in urban green space is more effective than other surfaces with high albedo, but the research of Yuan et al. (2017) found that excessive greenery will itself have a negative effect on the microclimate of the city by reducing ventilation [72]. In addition, climate factors are also an important influencing factor of USTE [73]. Alexandri and Jones (2008) developed a comprehensive simulation study of USTE, their results depicted that a greater reduction can be achieved in urban air temperature under a hotter and drier climate through using a green wall and green roof. They also found that, from the simulation, the same configuration of green wall and green roof, the reduction of air temperature in Moscow, Russia was below 4 K, while the value of Riyadh, Saudi Arabia, was above 11 K [73][74].

4.3. Building Layout for Controlling the USTE

The layout of the urban structure greatly influences the urban heat island effect [75][76]. Ali et al. (2016) applied CFD simulations in urban planning and landscape design at the scale of individual buildings and communities [77]. During urban planning, the spacing and orientation of buildings are calculated based on meteorological data. The overall layout and orientation of buildings generally conform to the prevailing wind direction in summer. This design can enhance the ventilation performance of buildings, thereby making the heat distribution more even because the wind can effectively dissipate heat. Thus, creating potential ventilation corridors is important for improving a USTE. Lin et al. 2017 introduced the concept of heat balance, expounding the influence of urban built environment factors on each component of energy flux (including net radiative flux, anthropogenic heat, convective (or turbulent) sensible heat flux, latent heat flux, stored energy, and net horizontal heat advection). Based on the perspective of urban geometry (Including land use intensity, building form, canyon geometry, space enclosure and descriptive characteristics) and vegetation, the impact of these influencing factors on the urban thermal environment on pedestrian height (at pedestrain level) is quantitatively studied [78]. Chen et al. (2004) simulated the outdoor wind and heat environments based on CFD and found that the outdoor temperature in residential areas is closely related to the architectural layout of these areas [79]. The downwind temperature in residential areas was higher than that in other areas, and the thermal environment was poor. Yang et al. (2011) found that the building layout, building density and green space proportion are the main factors that influence the thermal environment in residential areas during the day [80].

The number of buildings and the height of buildings are important factors that affect the urban wind and heat environments. In the use of CFD to simulate the thermal environment of buildings of different densities, it was found that increasing the number of buildings and reducing the height of buildings are conducive to creating a good wind environment [81]. Yang et al. (2015) simulated aspects of the residential outdoor environment (such as temperature, humidity and wind speed) in Shenzhen city, southern China, under different architectural layouts based on CFD technology [52]. The effects of a river and building layout on the outdoor thermal environment around riverside residential buildings were explored. Notably, when the vertical projected area of a building facing the prevailing wind was reduced, a ventilation and cooling corridor was created for winds in the direction of the river. In coastal cities, where high-rise buildings have low building ratios, sea breezes can flow through large spaces between buildings to lower the temperature [53]. Therefore, to a certain extent, it is possible to reduce the building ratio by establishing high-rise buildings to effectively reduce the ambient temperature and control the thermal environment [82].

The aspect ratio of buildings is another important factor that influences the urban thermal environment. Specifically, solar radiation plays a leading role in influencing the energy budget of buildings with different aspect ratios. As the aspect ratio increases, the effects of longwave radiation and heat flow conduction are continuously improved. Due to shading effects, the differences in the temperature distribution in space increase. The average radiant temperature can be 10 °C higher than the air temperature, and the radiant temperature in the direct sun area can reach up to 70 °C. When the aspect ratio reaches 2, sensible heat exchange is more obvious than heat conduction

[83] because as the height of the building increases, the solar radiation cannot reach the average height of the street or even the ground, radiation is reduced, and heat flow conduction increases.

4.4. Green Building Materials for Controlling the USTE

Research on the use of green building materials to control the thermal environment has shown that the selection of high-reflectivity building materials and pavement materials for the exterior walls and roofs of buildings has a significant effect in alleviating severe thermal environmental conditions [84][85]. For example, placing green vegetation on roofs has a positive effect on temperature, wind speed, and humidity [65]. Ferrari et al. (2020) performed CFD-based simulations of the wind-heat environment and found that the combination of high reflectivity and water-permeable pavement materials can reduce the surface temperature and create a comfortable thermal environment. In the case of low wind speeds, the use of high-reflectivity white asphalt compared to black asphalt can reduce the air temperature at a height of 1.5 m by 5 °C [20].

4.5. Ventilation Corridors for Controlling the USTE

Based on the wind field and USTE from CFD simulations, planning an urban ventilation corridor and analyzing the corresponding mechanism are hotspots of current research. The use of CFD simulations to accurately predict the wind environment in urban street canyons has achieved good performance [86], as demonstrated by wind tunnel tests. Shou et al. (2018) combined CFD and GIS technology to quantitatively study potential ventilation corridors in Changchun city [87]. Hsieh et al. (2016) used the FAI and LCP to predict city ventilation corridors by using ArcGIS and CFD technology to simulate and confirm the direction of ventilation corridors [55]. Ng et al. (2011) conducted a study in an area with low roughness to estimate urban ventilation corridors [88].

The ventilation environment can be adjusted to mitigate thermal environment problems. Good ventilation can reduce the heat accumulation in the center of an urban heat island, alleviate the urban heat island effect [60], and improve the comfort of the thermal environment [89]. Wind is the medium for heat exchange between a cold source and a heat source, and the main mechanism in alleviating the thermal effect is reflected by the following two factors. On the one hand, wind can effectively dissipate heat; on the other hand, wind can evenly distribute the cold air generated by water evaporation and vegetation transpiration. To mitigate the heat island effect, a reasonable ventilation corridor can be specifically designed according to different types of land use. Cold sources, such as green space and water bodies, should be built in the upwind areas of ventilation corridors, and the air will then flow through the low-temperature areas to cool the areas downwind.

References

1. Liu, H.; Zhou, G.; Wennersten, R.; Frostell, B. Analysis of sustainable urban development approaches in China. Habitat Int. 2014, 41, 24–32.
2. Yu, Z.; Yao, Y.; Yang, G.; Wang, X.; Vejre, H. Spatiotemporal patterns and characteristics of remotely sensed region heat islands during the rapid urbanization (1995–2015) of Southern

China. Sci. Total Environ. 2019, 674, 242–254.

3. Frayssinet, L.; Merlier, L.; Kuznik, F.; Hubert, J.L.; Milliez, M.; Roux, J.J. Modeling the heating and cooling energy de-mand of urban buildings at city scale. Renew. Sustain. Energy Rev. 2018, 81, 2318–2327.
4. Rizwan, A.M.; Dennis, L.Y.; Liu, C. A review on the generation, determination and mitigation of Urban Heat Island. J. Environ. Sci. 2008, 20, 120–128.
5. Wong, K.; Paddon, A.; Jimenez, A. Review of World Urban Heat Islands: Many Linked to Increased Mortality. J. Energy Resour. Technol. 2013, 135, 022101.
6. Yao, Y.; Chen, X.; Qian, J. Research progress on the thermal environment of the urban surfaces. Acta Ecol. Sin. 2018, 38, 1134–1147.
7. Guo, G.; Wu, Z.; Chen, Y. Evaluation of spatially heterogeneous driving forces of the urban heat environment based on a regression tree model. Sustain. Cities Soc. 2020, 54, 101960.
8. Li, Z.L.; Duan, S.B.; Tang, B.H.; Wu, H.; Ren, H.Z.; Yan, G.J.; Tang, R.L.; Leng, P. Review of methods for land surface tem-perature derived from thermal infrared remotely sensed data. J. Remote Sens. 2016, 20, 899–920.
9. Voogt, J.A.; Oke, T.R. Thermal remote sensing of urban climates. Remote Sens. Environ. 2003, 86, 370–384.
10. Zhang, R.; Sun, X.; Zhu, Z.; Su, H.; Tang, X. Total remote sensing information model of surface evaporation based on differential thermal inertia and its verification in Shapotou area of Gansu Province. Chin. Sci. 2002, D, 1041–1050.
11. Aflaki, A.; Mirnezhad, M.; Ghaffarianhoseini, A.; Ghaffarianhoseini, A.; Omrany, H.; Wang, Z.-H.; Akbari, H. Urban heat island mitigation strategies: A state-of-the-art review on Kuala Lumpur, Singapore and Hong Kong. Cities 2017, 62, 131–145.
12. Li, G.; Zhang, X.; Mirzaei, P.A.; Zhang, J.; Zhao, Z. Urban heat island effect of a typical valley city in China: Responds to the global warming and rapid urbanization. Sustain. Cities Soc. 2018, 38, 736–745.
13. Toparlar, Y.; Blocken, B.; Maiheu, B.; van Heijst, G. A review on the CFD analysis of urban microclimate. Renew. Sustain. Energy Rev. 2017, 80, 1613–1640.
14. Wang, X.; Li, Y. Predicting urban heat island circulation using CFD. Build. Environ. 2016, 99, 82–97.
15. Sidawi, B.; Hamza, N.; Khalid Setaih, P.C. CFD Modeling as a tool for Assessing Outdoor Thermal Comfort Conditions in Urban Settings in Hot Arid Climates. J. Inf. Technol. Constr. 2014, 248–269. Available online: https://www.itcon.org/papers/2014_14.content.080705.pdf (accessed on 12 October 2021).

16. Gan, C.; Zhuo, Z.; Zhang, H. Influence of Different Underlying Surfaces on Urban Thermal Environment Based on CFD Simulation. J. Shandong Agric. Univ. 2019, 50, 1021–1026.
17. Coseo, P.; Larsen, L. How factors of land use/land cover, building configuration, and adjacent heat sources and sinks explain Urban Heat Islands in Chicago. Landsc. Urban Plan. 2014, 125, 117–129.
18. Wang, X.; Li, Y.; Wang, K.; Yang, X.; Chan, P.W. A simple daily cycle temperature boundary condition for ground surfaces in CFD predictions of urban wind flows. J. Appl. Meteorol. Climatol. 2017, 56, 2963–2980.
19. Chen, H.-C.; Han, Q.; De Vries, B. Modeling the spatial relation between urban morphology, land surface temperature and urban energy demand. Sustain. Cities Soc. 2020, 60, 102246.
20. Ferrari, A.; Kubilay, A.; Derome, D.; Carmeliet, J. The use of permeable and reflective pavements as a potential strategy for urban heat island mitigation. Urban Clim. 2020, 31, 100534.
21. Alexander, P.; Mills, G.; Fealy, R. Using LCZ data to run an urban energy balance model. Urban Clim. 2015, 13, 14–37.
22. Radhi, H.; Fikry, F.; Sharples, S. Impacts of urbanisation on the thermal behaviour of new built up envi-ronments: A scoping study of the urban heat island in Bahrain. Landsc. Urban Plan. 2013, 113, 47–61.
23. Grossman-Clarke, S.; Schubert, S.; Clarke, T.A.; Harlan, S.L. Grimmond. Contribution of land use chang-es to near-surface air temperatures during recent summer extreme heat events in the Phoenix metropolitan area. J. Appl. Meteorol. Climatol. 2010, 49, 1649–1664.
24. Piscia, D.; Muñoz, P.; Panadès, C.; Montero, J.I. A method of coupling CFD and energy balance simulations to study humidity control in unheated greenhouses. Comput. Electron. Agric. 2015, 115, 129–141.
25. Takahashi, K.; Yoshida, H.; Tanaka, Y.; Aotake, N.; Wang, F. Measurement of thermal environment in Kyoto city and its prediction by CFD simulation. Energy Build. 2004, 36, 771–779.
26. Zhang, B.; Qian, G. Research progress of urban heat island effect. Sichuan Environ. 2007, 2, 88–91.
27. Li, K.; Yu, Z. Comparative and Combinative Study of Urban Heat island in Wuhan City with Remote Sensing and CFD Simulation. Sensors 2008, 8, 6692–6703.
28. Dimoudi, A.; Zoras, S.; Kantzioura, A.; Stogiannou, X.; Kosmopoulos, P.; Pallas, C. Use of cool mate-rials and other bioclimatic interventions in outdoor places in order to mitigate the urban heat island in a medium size city in Greece. Sustain. Cities Soc. 2014, 13, 89–96.
29. Fatima, S.F.; Chaudhry, H.N. Steady-state CFD modelling and experimental analysis of the local microclimate in Dubai (UAE). Sustain. Build. 2017, 2, 5.

30. Cao, X.; Onishi, A.; Chen, J.; Imura, H. Quantifying the cool island intensity of urban parks using ASTER and IKONOS data. Landsc. Urban Plan. 2010, 96, 224–231.
31. Zhang, M.; Bae, W.; Kim, J. The Effects of the Layouts of Vegetation and Wind Flow in an Apartment Housing Complex to Mitigate Outdoor Microclimate Air Temperature. Sustainability 2019, 11, 3081.
32. Chuanxiang, Y.I.; Jichao, H.U.; Xiaojun, L.I. Response analysis of land cover types on urban heat island effect. Bull. Surv. Mapp. 2018, 1, 72.
33. Chen, X.L.; Zhao, H.M.; Li, P.X.; Yin, Z.Y. Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. Remote Sens. Environ. 2006, 104, 133–146.
34. Jing, C.; Li, S.; Cao, S.; Ma, X. Study on influencing factors and influencing strength of urban green space relieving heat island effect—taking Beijing as an example. IOP Conf. Ser. Earth Environ. Sci. 2020, 601, 012033.
35. Bing-huai, L.I.N.; Da-Wen, Y.A.N.G. Numerical simulating of the heat island in Beijing. Shui Ke Xue Jin Zhan. 2007, 2, 258–263.
36. Huang, J.-M.; Chen, L.-C. A Numerical Study on Mitigation Strategies of Urban Heat Islands in a Tropical Megacity: A Case Study in Kaohsiung City, Taiwan. Sustainability 2020, 12, 3952.
37. Zhou, Y. Application of Computational Fluid Dynamics in Atmospheric Environment Simulation: A Case Study in Shenyang, China. In Proceedings of the International Symposium on Mechanical Engineering and Material Science, Jeju Island, Korea, 17–19 November 2016.
38. Liu, Y.; Lin, W.; Guo, J.; Wei, Q.; Shamseldin, A.Y. Shamseldin. The influence of morphological character-istics of green patch on its surrounding thermal environment. Ecol. Eng. 2019, 140, 105594.
39. Zhang, Y.; Zhan, Y.; Yu, T.; Ren, X. Urban green effects on land surface temperature caused by surface characteristics: A case study of summer Beijing metropolitan region. Infrared Phys. Technol. 2017, 86, 35–43.
40. Wang, G.Q.; Zheng, B.H.; Yu, H.; Peng, X. Green space layout optimization based on microclimate environment features. Int. J. Sustain. Dev. Plan. 2019, 14, 9–19.
41. Liu, Y.; Guo, J.; Wei, Q. Urban green space landscape patterns and thermal environment investigations based on computational fluid dynamics. Shengtai Xuebao/Acta Ecol. Sin. 2012, 32, 1951–1959.
42. Du, H.; Cai, Y.; Zhou, F.; Jiang, H.; Jiang, W.; Xu, Y. Urban blue-green space planning based on thermal environment simulation: A case study of Shanghai, China. Ecol. Indic. 2019, 106, 105501.

43. Sailor, D.J.; Lu, L. A top–down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas. Atmos. Environ. 2004, 38, 2737–2748.
44. Yuan, C.; Adelia, A.S.; Mei, S.; He, W.; Li, X.-X.; Norford, L. Mitigating intensity of urban heat island by better understanding on urban morphology and anthropogenic heat dispersion. Build. Environ. 2020, 176, 106876.
45. Wang, Y.N.; Sun, R.H.; Chen, L.D. Review on studies of anthropogenic heat emission. Ying Yong Sheng Tai Xue Bao J. Appl. Ecol. 2016, 27, 2024–2030.
46. Fan, H.; Sailor, D. Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: A comparison of implementations in two PBL schemes. Atmos. Environ. 2005, 39, 73–84.
47. He, X.-F.; Jiang, W.-M.; Chen, Y.; Liu, G. Numerical Simulation of the Impacts of Anthropogenic Heat on the Structure of the Urban Boundary Layer. Chin. J. Geophys. 2007, 50, 75–83.
48. Chen, Q.; Yang, X.; Ouyang, Z.; Zhao, N.; Jiang, Q.; Ye, T.; Qi, J.; Yue, W. Estimation of anthropogenic heat emissions in China using Cubist with points-of-interest and multisource remote sensing data. Environ. Pollut. 2020, 266, 115183.
49. Ching, J.; Aliaga, D.; Mills, G.; Masson, V.; See, L.; Neophytou, M.; Middel, A.; Baklanov, A.; Ren, C.; Ng, E.Y.Y.; et al. Pathway using WUDAPT’s Digital Synthetic City tool towards generating urban canopy parameters for multi-scale urban atmospheric modeling. Urban Clim. 2019, 28, 100459.
50. Lai, D.; Liu, W.; Gan, T.; Liu, K.; Chen, Q. A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. Sci. Total Environ. 2019, 661, 337–353.
51. Kubilay, A.; Derome, D.; Carmeliet, J. Coupled numerical simulations of cooling potential due to evapo-ration in a street canyon and an urban public square. J. Phys. Conf. Ser. 2019, 1343, 012016.
52. Yu, L.; Dai, D.; Xie, C. Layout Optimization of Riverside Residential Area Based on Thermal Comfort: A Case Study of Nanhua Village, Shenzhen. J. Landsc. Res. 2016, 8, 1–6.
53. Ashie, Y.; Kono, T. Urban-scale CFD analysis in support of a climate-sensitive design for the Tokyo Bay area. Int. J. Clim. 2010, 31, 174–188.
54. Tominaga, Y.; Sato, Y.; Sadohara, S. CFD simulations of the effect of evaporative cooling from water bodies in a micro-scale urban environment: Validation and application studies. Sustain. Cities Soc. 2015, 19, 259–270.
55. Hsieh, C.-M.; Huang, H.-C. Mitigating urban heat islands: A method to identify potential wind corridor for cooling and ventilation. Comput. Environ. Urban Syst. 2016, 57, 130–143.

56. Song, X.C.; Liu, J.; Ye, Z. Preliminary CFD Study on the Effects of Urban Water Body on Urban Thermal and Moisture Climate. Build. Sci. 2011, 27, 90–94.
57. Gülten, A.; Aksoy, U.T.; Öztop, H.F. Influence of trees on heat island potential in an urban canyon. Sustain. Cities Soc. 2016, 26, 407–418.
58. Dimoudi, A.; Nikolopoulou, M. Vegetation in the urban environment: Microclimatic analysis and benefits. Energy Build. 2003, 35, 69–76.
59. Vuckovic, M.; Maleki, A.; Mahdavi, A. Strategies for Development and Improvement of the Urban Fabric: A Vienna Case Study. Climate 2018, 6, 7.
60. Hou, C.; Hou, J.; Kang, Q.; Meng, X.; Wei, D.; Liu, Z.; Zhang, L. Research on urban park design combined with the urban ventilation system. Energy Procedia 2018, 152, 1133–1138.
61. Dimitris, F.; Catherine, B.; Aris, T.; Thomas, B.; Constantinos, K. Cfd study of ther-mal comfort in urban area. Energy Environ. Eng. 2017, 5, 8–18.
62. Gallo, K.P.; Tarpley, J.D. The comparison of vegetation index and surface temperature composites for urban heat-island analysis. Int. J. Remote Sens. 1996, 17, 3071–3076.
63. Gupta, R.; Prasad, S.; Viswanadham, T. Estimation of Surface Temperature over agriculture region. Adv. Space Res. 1997, 19, 503–506.
64. Weng, Q.; Lu, D.; Schubring, J. Estimation of land surface temperature–vegetation abundance rela-tionship for urban heat island studies. Remote Sens. Environ. 2004, 89, 467–483.
65. Vuckovic, M.; Kiesel, K.; Mahdavi, A. The Extent and Implications of the Microclimatic Conditions in the Urban Environment: A Vienna Case Study. Sustainability 2017, 9, 177.
66. Lin, B.; Li, X.; Zhu, Y.; Qin, Y. Numerical simulation studies of the different vegetation patterns' effects on outdoor pedestrian thermal comfort. J. Wind. Eng. Ind. Aerodyn. 2008, 96, 1707–1718.
67. Xiaolong, L.; Yingbao, Y.; Lijuan, C.; Yong, Z. Research on the influence of urban green space distribution on the thermal environment based on RS and CFD simulation. Remote Sens. Technol. Appl. 2016, 31, 1150–1157.
68. Zhao, T.; Fong, K.F. Characterization of different heat mitigation strategies in landscape to fight against heat island and improve thermal comfort in hot–humid climate (Part I): Measurement and modelling. Sustain. Cities Soc. 2017, 32, 523–531.
69. Morakinyo, T.E.; Lau, K.K.; Ren, C.; Ng, E. Performance of Hong Kong's common trees spe-cies for outdoor temperature regulation, thermal comfort and energy saving. Build. Environ. 2018, 137, 157–170.
70. Zhang, L.; Zhan, Q.; Lan, Y. Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: A case study in Wuhan residential quarters.

Build. Environ. 2018, 130, 27–39.

71. Lin, H.; Xiao, Y.; Musso, F.; Lu, Y. Green Façade Effects on Thermal Environment in Transitional Space: Field Measurement Studies and Computational Fluid Dynamics Simulations. Sustainability 2019, 11, 5691.
72. Yuan, J.; Emura, K.; Farnham, C. Is urban albedo or urban green covering more effective for urban micro-climate improvement? A simulation for Osaka. Sustain. Cities Soc. 2017, 32, 78–86.
73. Hami, A.; Abdi, B.; Zarehaghi, D.; Bin Maulan, S. Assessing the thermal comfort effects of green spaces: A systematic review of methods, parameters, and plants' attributes. Sustain. Cities Soc. 2019, 49, 101634.
74. Alexandri, E.; Jones, P. Temperature decreases in an urban canyon due to green walls and green roofs in di-verse climates. Build. Environ. 2008, 43, 480–493.
75. Hsieh, C.-M.; Aramaki, T.; Hanaki, K. Managing heat rejected from air conditioning systems to save energy and improve the microclimates of residential buildings. Comput. Environ. Urban Syst. 2011, 35, 358–367.
76. Krüger, E.; Minella, F.; Rasia, F. Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil. Build. Environ. 2011, 46, 621–634.
77. Cheshmehzangi, A. Multi-spatial environmental performance evaluation towards integrated urban design: A procedural approach with computational simulations. J. Clean. Prod. 2016, 139, 1085–1093.
78. Lin, P.; Gou, Z.; Lau, S.S.; Qin, H. The impact of urban design descriptors on outdoor ther-mal environment: A literature review. Energies 2017, 10, 2151.
79. Chen, H.; Ooka, R.; Harayama, K.; Kato, S.; Li, X. Study on outdoor thermal environment of apartment block in Shenzhen, China with coupled simulation of convection, radiation and conduction. Energy Build. 2004, 36, 1247–1258.
80. Yang, F.; Lau, S.S.; Qian, F. Urban design to lower summertime outdoor temperatures: An empirical study on high-rise housing in Shanghai. Build. Environ. 2011, 46, 769–785.
81. Li, P.; Yan, T.; Deng, N. On the influence of distribution of high-rise buildings on outdoor wind and thermal environment. Urban Archit. 2017, 2017, 20.
82. Priyadarsini, R.; Hien, W.N.; David, C.K.W. Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island. Sol. Energy 2008, 82, 727–745.
83. Schrijvers, P.; Jonker, H.; de Roode, S.; Kenjereš, S. On the daytime micro-climatic conditions inside an idealized 2D urban canyon. Build. Environ. 2020, 167, 106427.

84. Santamouris, M.; Haddad, S.; Saliari, M.; Vasilakopoulou, K.; Synnefa, A.; Paolini, R.; Ulpiani, G.; Garshasbi, S.; Fiorito, F. On the energy impact of urban heat island in Sydney: Climate and energy potential of mitigation technologies. Energy Build. 2018, 166, 154–164.
85. Synnefa, A.; Karlessi, T.; Gaitani, N.; Santamouris, M.; Assimakopoulos, D.N.; Papakatsikas, C. Experi-mental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate. Build. Environ. 2011, 46, 38–44.
86. Allegrini, J.; Dorer, V.; Carmeliet, J. Buoyant flows in street canyons: Validation of CFD simulations with wind tunnel measurements. Build. Environ. 2014, 72, 63–74.
87. Chang, S.; Jiang, Q.; Zhao, Y. Integrating CFD and GIS into the development of urban ventilation corri-dors: A case study in Changchun City, China. Sustainability 2018, 10, 1814.
88. Ng, E.; Yuan, C.; Chen, L.; Ren, C.; Fung, J.C. Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong. Landsc. Urban Plan. 2011, 101, 59–74.
89. Huang, H.C.; Lin, F.T.; Hsieh, C.M. A simple method for designation of urban ventilation path by using agent analyst in GIS—A study of Tainan. In Proceedings of the Conference on Sustainable Business, Energy and Development in Asia, Hiroshima, Japan, 17–19 March 2014.

Retrieved from https://encyclopedia.pub/entry/history/show/36551