Urban Microclimate Modeling with ENVI-met: A Review on Green Infrastructure and Climate-Responsive Urban Design

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Abstract

In recent years, as the effects of global climate change have begun to be felt more in cities, the temperature in cities has increased and thermal comfort has decreased. In cities facing these problems, nature-based strategies in the form of green infrastructure applications and sustainable urban design approaches stand out in improving microclimatic conditions. ENVI-met is a three-dimensional simulation model widely used to perform microclimatic analyses and evaluate the thermal effects of green areas, planting types and surface coverings in line with various scenarios.

In this compilation study, what ENVI-met software is, its data entry requirements, limitations, advantages and disadvantages, current academic studies conducted using ENVI-met software have been examined and the effects of different planting strategies, green infrastructure elements in the form of green roofs, urban afforestation and material choices on urban microclimate have been evaluated.

The findings show that ENVI-met is effective in predicting the effects of different design alternatives on microclimate, especially in small-scale urban areas, and that the heat effect can be reduced in cities with green infrastructure scenarios, and that it has a high potential to provide shading and increase thermal comfort. However, the disadvantages of the model such as the calibration process, insufficient local climate data, simulation time and limited plant database should also be taken into account.

In conclusion, this study emphasizes that ENVI-met modeling is a powerful tool for urban climate-friendly designs, and also draws attention to the importance of green infrastructure strategies in sustainable planning processes. It is recommended that future research test the applicability of the model in different climate zones and larger-scale projects.

Keywords: Thermal comfort, Microclimate, ENVI-met, KIA, Climate change

Introductıon

The subject of climate change first began to be included in scientific studies in 1827 when Joseph Fourier emphasized that the atmospheric layer was important in determining the temperature on earth and said that the atmosphere undertook a greenhouse-like function

(Dispensa and Brulle, 2003; Yuca, 2025). After the 19th century, with the increase in greenhouse gas accumulation in urban areas where human density increased, the importance of climate change was better understood and it was thought that one of the reasons for this could be humans.

Throughout history, people have affected the climate positively or negatively with the choices they made, affecting the livability and comfort level of living spaces. With the industrial revolution, the need for building stock increased due to the rapid increase in the population in cities. This rapid increase was quickly responded to by destroying the open-green areas and natural areas, which are the natural land cover in cities, and constructing irregular and unplanned structures in the places of these natural areas. As a result, cities have turned into areas with few open-green areas and natural areas and many impermeable surfaces. Thus, the topography, ecological structure and atmospheric features in cities have changed and have begun to have a separate ecology, a different climate and a different atmosphere from their surroundings (Rios and Ramamurthy, 2024). Since the land texture, morphological structure, amount of open-green areas and many other features in urban areas are different from each other, the negative effects of climate change vary from region to region. In this direction, studies on the negative effects of climate change are generally carried out separately for 4 different scales (Oke, 2002; Erell et al., 2012). These scales are macro scale, meso scale (urban scale), local scale and micro scale (Oke and Cleugh, 1987; Yuca, 2025). (Figure 1.).

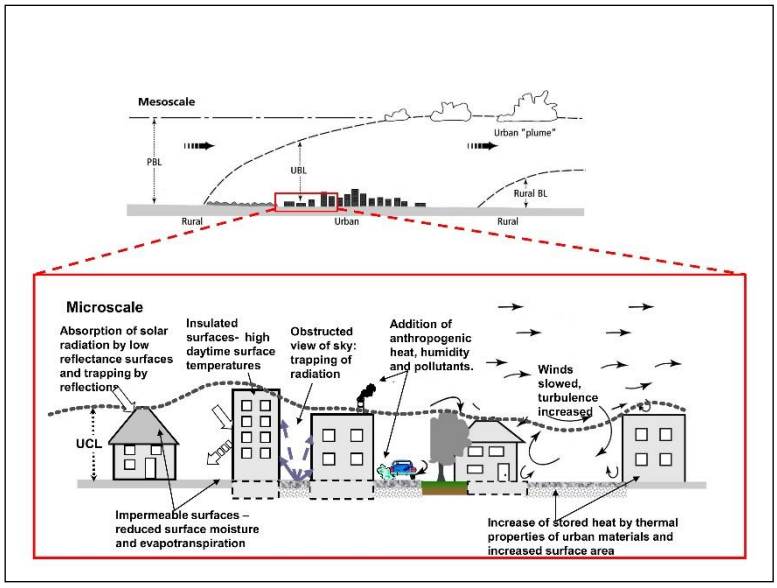


Figure 1. Impact areas of atmospheric events at different scales (Anonymous 2025a).

With the change in land use in cities, the gaseous and particulate components emitted into the atmosphere have changed, causing the composition of the air in urban areas to change and higher temperatures, lower humidity and weak wind movements to be seen in cities (Çağlak et al., 2022). As a result, the negative effects of global warming have begun to be felt more in urban settlements that have their own climate (Dodken et al., 2016). The reason for this is; the floor heights of buildings in urban areas, the form and density of buildings, the amount of shade

created by buildings and trees affecting the wind flow, the street width ratio, the ability of structural elements to reflect sunlight and many other factors change the heat flows of radiant temperatures (Oke and Cleugh, 1987). The biggest change that occurs at this scale is the Urban Heat Island (UHI) effect, which causes the formation of regional temperatures, which is seen as the biggest problem today (Tozam and Karaca, 2018). KIA is the situation where the natural land cover in urban areas changes and is replaced by impermeable hard surfaces, the air pollution in the region is trapped in the urban atmosphere due to increased vehicle traffic, and the air temperature values of urban settlements are higher than the surrounding rural areas due to the increase in carbon dioxide and other greenhouse gas emissions as a result of increased anthropogenic activities (Landsberg, 1981). (Figure 2).

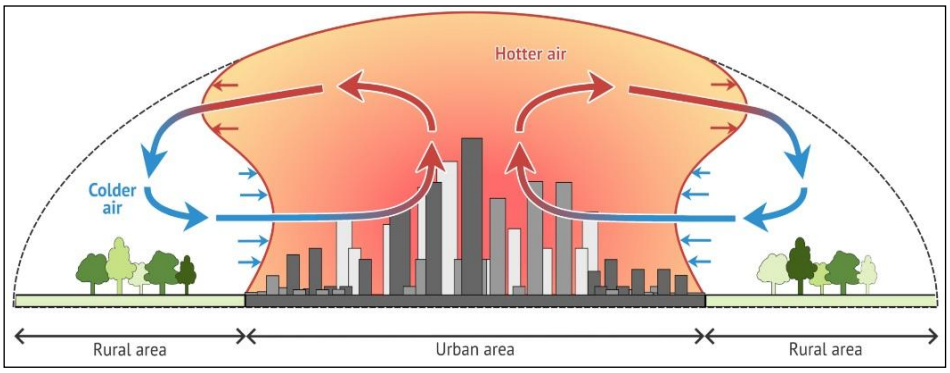


Figure 2. Temperature difference between urban and rural settlements (KIA) (Anonymous 2025b).

Due to the increasing heat waves in cities due to the increase in the HIA effect, heavy rains, droughts and other extreme weather disasters in urban settlements (Ganeshan et al., 2013), increased heat strokes, increased mortality rates (Başa et al., 2024), increased thermal comfort in the city and increased mental health problems that may occur as a result of stress, depression and anxiety in people living in cities, high temperatures increase aggressive tendencies in people (Ranson, 2014), and the experience of the elderly in cognitive skills decreases when they are exposed to air pollution for a long time (Dodgen et al., 2016).

The HIA effect is an increasing source of concern in densely populated cities due to the negative effects on human health and thermal comfort by increasing environmental degradation in urban settlements. In order to find a solution to this problem, studies have begun to be carried out for settlement areas with different scales and settlement typologies. As a result of these studies, it has been revealed that outdoor spaces with natural landscape elements replacing structural areas that cause the KIA effect have healing and renewing effects on people's physical and mental health, reduce mental fatigue and increase people's focus, the time spent in these spaces effectively reduces stress and improves the individual's psychological and physiological performance (Ulrich et al., 1991), sleep patterns improve in elderly individuals whose outdoor use increases, they say they have less pain, and the symptoms of dementia and Alzheimer's diseases slow down (Jacobs et al., 2008). As can be seen from the aforementioned studies, positive effects on the health of people using outdoor spaces with less structural density and more natural landscape texture have been determined.

In these studies, the importance of green infrastructure systems in reducing KIA effects has generally emerged. Green infrastructure systems contribute to reducing the impact of KIA by playing an important role in ensuring the health, thermal comfort and sustainability of both present and future urban environments with planning and design approaches focusing on the protection of existing natural and green areas (Shakouri, 2016; Ortaçeşme and Altunbey, 2022). This system includes providing shading in outdoor areas, managing the use of water, and creating green roofs and green walls. (Figure 3.).

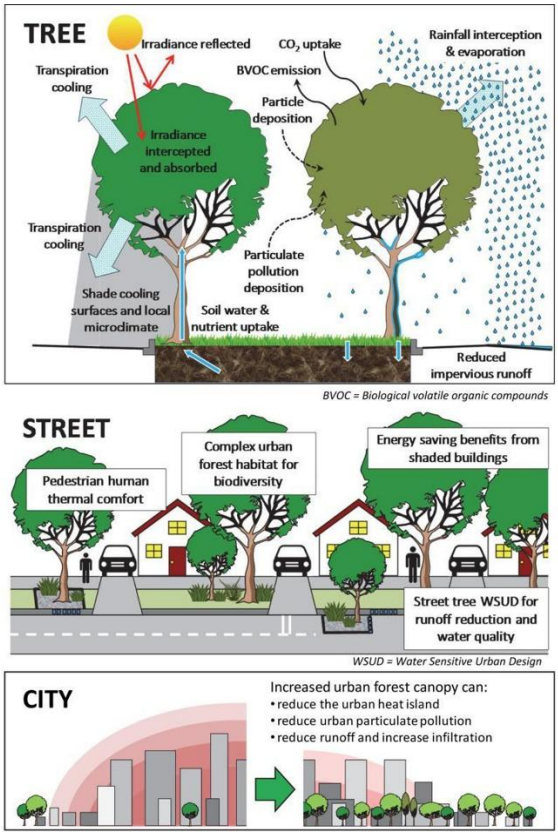


Figure 3. Ecosystem service of trees at street and urban scale (Livesley et al., 2016).

Green infrastructure systems, which have an important place in reducing the KIA effect, include various applications such as preserving and increasing natural green areas in urban areas, afforestation, grassing, vegetation, water management and energy efficiency. The effects of these systems vary according to their scale. For example, green roofs installed on building roofs reduce the KIA at the building level, while larger-scale green areas such as parks and groves can reduce the KIA effect in the immediate vicinity (Farzaneh and Heidari ,2023; Johnson, 2025).

Due to the geometry and density of urban areas and the heating and radiation properties formed on their surfaces, the KIA effects in urban areas are different from each other, so green systems cannot have the same effect in every urban settlement area. Therefore, studies have been carried out recently to reduce the KIA effect in cities by creating different designs using green systems in different modeling programs.

In this context, sustainable urban design approaches and microclimate analysis tools are increasingly gaining importance. ENVI-met is a model that can perform 3D microclimate

simulations and is widely used in the analysis of various urban scenarios (Yuca, 2025). This study aims to evaluate the contributions of ENVI-met software to climate-focused design decisions by compiling its use in different application areas.

For this purpose, firstly, the general features of ENVI-met microclimate simulation, its areas of use, and its limitations are emphasized. Secondly, current studies conducted using this model are given. Finally, suggestions regarding the areas of use of this model are made in the conclusion and suggestions section.

1. ENVI-met Model: General Features and Methodological Structure

In this section, the general features of ENVI-met software, the areas of use, software inputs and outputs, and finally the advantages and disadvantages of the software are evaluated.

ENVI-met, which was developed by Michael Bruse in 1998 for urban microclimate simulations and is a 3D modeling software, is widely used in the fields of planning, environmental design, climate-focused design, architecture, and building design (Bruse and Fleer, 1998). This software offers the opportunity to perform microclimatic analyses by integrating atmospheric processes, vegetation, surface materials and building geometries in urban areas.

This software, which is a 3D microclimate simulation model that integrates various atmospheric, physiological and environmental processes at high spatial and temporal resolution, has one of its main application areas as the analysis of the impact of buildings on urban microclimate (Ali-Toudert and Mayer, 2004). The size and shape of buildings greatly affect human thermal comfort at street level, as they affect wind flow and solar access in the streets. Due to the difficulty of living conditions and deterioration of health status in areas where thermal comfort conditions are not good, this model has recently been widely used in conducting studies in areas where urban texture is high and the resulting KIA effect is high. The reason for its intensive use in studies is that the software consists of sub-models specially adopted to solve unique physical mechanisms in the background (Vurro and Carlucci, 2024). These sub-models;

• Long and short wave radiation fluxes taking into account shading,

• Radiation reflection from building facades, ground materials and vegetation,

• Evaporation and sensible heat fluxes from vegetation,

• Evaporation from water surfaces,

• Diffusion of chemical species,

• Distribution of particles,

• Heat and water transfer within the soil mass,

• Body/skin airflow interactions for thermal comfort calculations (Vurro and Carlucci, 2024).

Provided that the software settings are correctly defined, this tool is useful for predicting and evaluating KIA effects in urban settlements with reasonable accuracy. The latest version of the model, ENVI-met BIO Science 5.7.2, has advantages as well as disadvantages. In this respect, the data entered into the model, the findings obtained as a result of the simulation, the advantages and disadvantages of the model are mentioned.

• **Model Input Data:** The software performs simulations by entering various data such as meteorological data (e.g. air temperature, wind speed and direction, humidity), surface materials (albedo, heat capacity), plant characteristics (height, leaf area index) and building geometries.

• **Model Outputs:** ENVI-met software creates maps that provide spatial and temporal distributions of microclimatic parameters such as air temperature, surface temperature, wind speed and direction, relative humidity, mean radiant temperature (MDRT) and physiological equivalent temperature (FES).

• **Model Advantages:** It can simulate microclimatic conditions in urban areas at high resolution, which helps to make more conscious design decisions.

• It can be used in many areas such as green infrastructure planning,

• Reducing the KIA effect,

• Open space design and material selection.

• Since the simulation output is supported by 3D visualization tools, it is easier for users to perceive.

• **Disadvantages of the Model:** Since high-resolution simulations are obtained as model output, the processes take a long time.

• Since the processing time is long, mostly small-scale studies are carried out.

• The software may give errors when modeling for areas with low wind data.

• In order to obtain accurate results, the model must be carefully calibrated, which requires experience and expertise.

• In the event of any power outage, the model is reset and needs to be restarted.

• Since the plant species used in the model are not sufficient, the current situation of each study area cannot be simulated one-to-one.

• Since the implementation of the roof garden, which is a green system model, is more detailed, this process requires expertise.

2. Current Studies Using ENVI-met Climate Simulation

In this section, literature examples and findings obtained for different application areas of ENVI-met software, which is widely used in urban microclimate studies, are summarized (Tablo 1.);

Table 1. Studies Conducted Using ENVI-met Software

Application Area	Study Year	Study Title	Main Findings
Green Infrastructure	Irmak et al., 2020	Analysis of different urban spaces on thermal comfort in cold regions: A case from Erzurum.	"The study revealed that in cities with cold climates, water surfaces positively contribute to thermal comfort during the summer months, whereas they increase cold stress during the winter. In contrast, dense green infrastructure was found to have a balancing effect on urban thermal comfort in both summer and winter seasons.
Green Infrastructure	Farzaneh and Heidari ,2023	Evaluation of the Role of Green Infrastructure in Microclimate and Building Energy Efficiency	Green infrastructure interventions have been shown to reduce ambient temperatures and enhance thermal comfort.
Green Infrastructure	Farrag and Mehana 2024	*The impact of green infrastructure on urban heat island phenomenon in existing cities*.	It was determined that planting trees in a grid pattern reduced the air temperature by an average of 0.7 °C, the mean radiant temperature (MDRT) by 9 °C, and the predicted mean vote (PMV) by 0.6.
Green Infrastructure	Fan et al., 2025	The impact of vegetation layouts on thermal comfort in urban main streets: A case study of Youth Street in Shenyang.	It was found that air temperature, mean radiant temperature (MDRT), and sky view factor (SVF) have a positive correlation with the FES value. Additionally, street trees were observed to reduce air temperature and wind speed while increasing humidity levels.
Green Infrastructure	Yilmaz et al., 2025	Investigating the effect of blue–green infrastructure on thermal condition—Case study: Elazığ, Turkey.	The integrated use of blue-green infrastructure elements has been found to be effective in reducing the Urban Heat Island (UHI) effect and enhancing thermal comfort.
Green Infrastructure and the Use of Materials	Tan et al., 2021	The potential of vegetation to mitigate urban heat islands depends on local surface type and shading.	It has been found that the use of high-albedo materials along with vegetation can reduce the Urban Heat Island (UHI) effect on the land surface, and that planting vegetation on shaded surfaces provides marginal additional cooling.
Green Infrastructure and the Use of Materials	Cuce et al., 2025	Towards sustainable and climate-resilient cities: Mitigating urban heat islands through green infrastructure.	Strategically placed trees have been shown to provide significant shading and evapotranspiration benefits.
Green Infrastructure and the Use of Materials	Zhang et al., 2025	Quantifying the impact of building material stock and green infrastructure on urban heat island intensity.	It has been observed that areas with high heat-absorbing materials (e.g., dark-colored asphalt) exhibit a more pronounced Urban Heat Island (UHI) effect, whereas green infrastructure elements (e.g., trees, green roofs) mitigate this impact.
Use of Materials	Ouyang et al., 2022	Evaluating the thermal-radiative performance of ENVI-met model for green infrastructure typologies: Experience from a subtropical climate.	Surface materials with high albedo values have been found to reduce surface temperatures and enhance thermal comfort.
Use of Materials	Johnson, 2025	Cool roofs could fight Atlanta's rising heat.	It has been determined that cool roofs can reduce temperatures citywide by an average of 1.4°C (2.5°F) and that this application can help mitigate the Urban Heat Island (UHI) effect.
Use of Materials	Smithvand Lee, 2024	On the role of the building envelope on the urban heat island effect.	High-reflectance roofing and façade materials have been observed to reduce building surface temperatures and mitigate increases in ambient temperature.
Urban Morphology	Xiang et al., 2023	Exploring the Correlation between Urban Microclimate Simulation and Urban Morphology: A Case	It was found that high-rise residential buildings increase outdoor temperatures, while open spaces play a significant role in reducing neighborhood temperatures.

		Study in Yeongdeungpo-gu, Seoul.	
Urban Morphology	Yun et al., 2023	Developing a three-dimensional urban surface model for spatiotemporal analysis of thermal comfort with respect to street direction.	It was determined that a small change in street orientation has a significant impact on pedestrian thermal comfort.

As shown in Table 1, studies conducted using the ENVI-met software indicate that green infrastructure systems generally contribute to urban environments by providing shading, thereby reducing Mean Radiant Temperature (MRT) values and enhancing thermal comfort. Strategically placed vegetation, particularly trees positioned in a way that does not obstruct wind flow based on settlement characteristics, has been found to decrease air temperature and mitigate the Urban Heat Island (UHI) effect while increasing humidity levels. Furthermore, the use of light-colored materials reduces heat retention, leading to a decrease in air temperature.

3. Conclusion and Recommendations

Cities, due to their dense populations and their role as centers for major economic activities such as industry, are both a significant contributor to climate change and among the most affected by its impacts. While it is often considered that the increasing effects of climate change in recent years have led to a decline in thermal comfort and negatively impacted human health in urban areas, the cumulative effects of these micro-scale changes have reached a global dimension. Thus, the issue is no longer limited to micro-scale climate change but has evolved into a global climate change problem affecting the entire planet.

To address the global climate change crisis now a problem that transcends national boundaries—a holistic approach should be adopted that emphasizes local-scale actions and even individual-level efforts, rather than relying solely on global-scale strategies. In this context, over the past 50 years, research-based software tools have been developed and made available to scientists to analyze micro-scale climatic conditions in various urban settlements.

Among these tools, the ENVI-met microclimate simulation software has recently gained prominence due to its ability to contribute effectively to sustainable urban design processes at the microclimatic level and to deliver highly accurate results. Based on the findings of this study, several recommendations are proposed regarding the use of ENVI-met in mitigating or preventing the effects of climate change:

- First, since each settlement area has unique morphological characteristics, ENVI-met should be tested with a wider range of scenarios across different climate zones;
- Emphasis should be placed on ENVI-met's effectiveness as an analytical tool in green infrastructure design;
- Resilient design strategies for critical areas should be developed using ENVI-met in anticipation of future heatwaves;
- Modeling new residential areas can help predict and visualize potential heat stress scenarios;

- ENVI-met should be employed as a decision-support tool for urban planners, landscape architects, and policymakers.

The use of climate modeling tools, particularly in green infrastructure planning, is of critical importance in enhancing thermal comfort, creating sustainable living environments, and reducing energy consumption.

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