



Quantifying the aggravation and mitigation of urban heat island through differential dynamic changes in impervious surface

Tianyu Xu ^a, Jie Gong ^{a, b}  , Zhihui Yang ^a, Yixu Wang ^a, Tiantian Jin ^a, Imanmadi Duman ^c, Ermekov Farabi Kerimbaevich ^c

[Show more](#) 

 Share  Cite

<https://doi.org/10.1016/j.scs.2025.106680> 

[Get rights and content](#) 

Highlights

- A novel mapping approach for dynamic impervious surface percentage was proposed.
- A time-series correction method was optimized for various changes trends.
- The impact of impervious surface change types on the trend of urban heat island effect was explored.
- Reducing impervious surfaces is conducive to mitigating the urban heat island effect.
- Arid regions exhibit unique changes in urban heat island effect.

Abstract

Impervious surfaces changes significantly impact urban heat island patterns during rapid urbanization. However, existing extraction models face challenges in capturing the temporal impervious surfaces dynamics and identifying reverse changes, mainly due to regional heterogeneity and temporal instability. Moreover, the impacts of these changes on surface urban heat island intensity (SUHII) trends and its patterns remain unclear. Therefore, this study developed a framework for estimating dynamic impervious surface percentage (DISP) by integrating machine learning and time optimization. The framework was used to quantify the SUHII trend under four types of impervious surface changes (increased, decreased, unchanged, and other). This classification can investigate the distinct thermal environmental responses associated with different DISP. Firstly, spatiotemporal consistency screening and extraction rules were designed to generate training samples. Subsequently, multi-temporal image fusion strategies were implemented, and regionally adaptive impervious surface percentage estimation models were constructed based on multiple feature combinations. Additionally, a time-series correction method was introduced to optimize DISP across different change trajectories. Finally, the dynamic trends of SUHII were captured under time series changes and regional differences,

based on various impervious surface change types. The results show that DISP can achieve continuous and accurate estimations ($R^2 = 0.848$, $RMSE = 0.106$), outperforming existing products. Different types of impervious surface changes exhibit distinct thermal responses, with increased DISP intensifying the heat island effects and decreased DISP mitigating them. These effects are more pronounced in tropical and temperate zones than in arid regions. And high-density impervious surfaces also correspond to higher temperatures. Consequently, DISP provides robust and continuous reference for monitoring urban impervious surface dynamics and associated thermal environmental changes within cities.

Introduction

Urbanization has drastically altered natural land cover, replacing vegetated or bare surfaces with impervious materials such as concrete, asphalt, and rooftops. These impervious surfaces disrupt the natural hydrological cycle, alter surface energy balance, and reduce vegetation cover, thereby intensifying the urban heat island (UHI) effects (Hu et al., 2024; Zhang et al., 2024a). The combined impacts of rapid land use conversion, population growth, and climate change have increased the complexity of urban thermal environments (Zhang et al., 2024b). In rapidly developing regions, urban expansion has surpassed environmental regulation, leading to fragmented land cover transitions and highly heterogeneous urban thermal environments. Regarding global climate change, these transformations are exacerbating heat stress and reducing urban climate resilience (Ahmad et al., 2024; Rentschler et al., 2023). Understanding the dynamic changes in impervious surfaces is crucial to accurately assess the trend and scale of the UHI, especially for impervious surfaces under different change types and trends within cities (Huang et al., 2019). Moreover, considering that the dynamic evolution of impervious surfaces is a key driver of UHI variability, improving the temporal consistency and spatial accuracy of impervious surface data is essential for advancing long-term thermal environment studies (Wang et al., 2024). Therefore, the precise mapping of dynamic impervious surfaces and the further analysis of thermal environmental patterns are necessary, which are critical to supporting sustainable urban development.

Previous research has used impervious surface information to model and assess UHI effects (Li & Chen, 2023). Existing strategies ignore the heterogeneity of the surface urban heat island intensity (SUHII) caused by complex impervious surface changes (Du et al., 2024). Although global or regional impervious surface products are becoming more accessible, their applicability in urban climate studies remains limited. Coarse-resolution products rely on categorical classifications and are unable to capture the continuous variation in impervious surface density that drives thermal heterogeneity (Xu et al., 2022). Medium-resolution products often face challenges in data consistency and tend to overestimate the built-up areas within urban interiors, weakening the capacity to quantify the true relationship between impervious surfaces and SUHII (Chakraborty & Lee, 2019). Additionally, most studies have focused on surface temperature changes in expansion areas, which are typically used to identify UHI associated with outward urban growth (Peng et al., 2024). However, these approaches tend to oversimplify surface change trajectories and neglect intra-urban heterogeneity. For example, localized reductions in impervious surfaces may occur due to the development of green infrastructure, land restoration, or building demolition, even as urban sprawl continues in other areas (Gao et al., 2024). Moreover, impervious surface density plays a key role in shaping urban thermal environments by influencing surface thermal inertia and energy exchange processes (Xu et al., 2024). Recent studies have increasingly highlighted the critical role of green cover and built-up density in modulating urban thermal behavior (Wang et al., 2025). These spatially and temporally variable impervious surfaces dynamics pose challenges to accurately capturing urban thermal responses. Therefore, a method to accurately obtain the dynamic impervious surfaces is needed to construct a comprehensive spatiotemporal framework between urban surface changes and thermal responses.

With the increase in data availability and advancement in processing technology, time series impervious surface extraction has become feasible. Generally, there are two primary approaches: continuous change detection and multi-temporal independent extraction. Continuous change detection relies on a detection strategy to identify change points in time-series images. For example, Landsat-based Detection of Trends in Disturbance and Recovery (LandTrendr), and Continuous Change Detection and Classification (CCDC) (Brown et al., 2020; Murillo-Sandoval et al., 2021). However, the method is less effective for capturing gradual transformations, and is more commonly used for classification tasks (Pasquarella et al., 2022). Impervious surface percentage conversion is not abrupt (Fan et al., 2022; Sun et al., 2022). Continuous change detection typically relies on related indicators to identify dynamic changes (Guan et al., 2020). The effectiveness depends on accurate data and densely collected multi-temporal images. However, obtaining continuous

cloud-free images over large-scale areas can be challenging. And the method may be limited in the context of complex urban surface dynamics. Multi-temporal independent extraction involves establishing predictions for multiple periods to achieve dynamic impervious surface mapping based on change rules (Liu et al., 2020a). The predictive model plays a crucial role in the accuracy and includes techniques such as spectral mixture analysis, spectral index, traditional image classification, deep learning, and machine learning. Spectral mixture analysis is difficult to apply to large areas, because selecting optimal end-elements is more difficult and subjective (Shao et al., 2022; Zhang et al., 2023). Methods based on spectral index are simpler and faster; however, the identification of the optimal threshold still leads to poor applicability (Dvornikov et al., 2023). Traditional classification methods are not suitable for extracting long-term mapping due to their low accuracy (Misra et al., 2020). Deep learning can enhance precision, particularly for high-resolution images (Wu et al., 2023). Finally, machine learning can be employed to interpret long-time series images for estimating impervious surface percentage. Feature construction is the key to building the extraction model, while sample quality affects prediction results significantly (Schneider, 2012). It is also noteworthy that optimizing independently extracted results remains essential for achieving consistent and temporally accurate dynamic mapping (Huang et al., 2021a; Li et al., 2015).

Land cover transformations predominantly shift toward a single land type within a given timeframe, often involving either the expansion or reduction of impervious surfaces (Qiu et al., 2024). Many studies develop logic optimization strategies based on the assumption that changes in impervious surfaces are irreversible (Li et al., 2018). However, such approaches often overlook localized decreases in impervious surfaces, which can occur sporadically or gradually in large-scale, long-term monitoring (Zhu et al., 2022). More rational dynamic mapping strategies are needed to accommodate both progressive and regressive shifts. Impervious surface features are primarily derived from spectral features and temporal information (Ren et al., 2024). Temporal information improves the interpretation effect and mitigates interferences such as clouds and rainfall (Dong et al., 2024). For example, multi-seasonal features become crucial for representing diverse information (Zeng et al., 2020). Notably, multi-temporal information can be extracted by selection-based and transformation-based methods. Selection-based methods define specific periods for feature extraction, which can perform well in small-scale areas with consistent phenology (Dvornikov et al., 2023). The percentile synthesis method is a transformation-based approach, which sorts time-series data to extract features (Zhang et al., 2021). Nevertheless, this method does not accurately capture the regional consistency of seasonal information (Lian et al., 2021). Large-scale regions exhibit diverse seasonal changes (Liu et al., 2024). On the other hand, multi-source data provides richer information, such as nighttime lighting and population distribution, which provides a possibility for estimating impervious surfaces percentage (Shi et al., 2023b). To address the issue of time-series samples, scholars have proposed various methods (Huang et al., 2020; Yang et al., 2021). Sample migration requires high-quality samples and raw data (Cui et al., 2023). Manual labeling is time-consuming and labor-intensive (Huang et al., 2021b). Exportation from existing products relies on refinement rules and pre-existing impervious surface data, which is highly feasible for extensive mapping (Zhang et al., 2020; Zheng et al., 2023). For example, the union method is used to capture time-series samples with consistency (Zhang et al., 2024c). However, relying solely on temporally stable reference data diminishes sample diversity. Additionally, spatial coverage and temporal consistency must also need to be taken into consideration.

Reasonable and accurate time series in impervious surfaces are critical indicators for describing the trend and pattern of UHI effect. Therefore, we proposed a novel method for estimating DISP, aiming to assist in monitoring the spatiotemporal differences in SUHII under changes in impervious surface. Specifically, the approach begins by utilizing reference samples from existing impervious surface products, which are then optimized through temporal filtering and extraction. This improvement has increased efficiency and reduced inconsistencies caused by manual intervention. Additionally, considering regional heterogeneity and phenological seasonal information, we integrate multi-source data and multi-temporal features, and design a variety of feature combination schemes and machine learning inversion models. A regionally adaptive model for estimating the percentage of impervious surface was then developed for each year. Subsequently, the temporal optimization strategy is employed to correct impervious surface changes under different change trends, which reduces inconsistencies. Finally, we quantified the trends of SUHII for impervious surfaces that increased, unchanged, decreased, or other. Moreover, we further explored the differences in SUHII across climate regions and impervious surface densities. This approach enhances the accuracy and reliability of impervious surface mapping and provides a quantitative framework for characterizing SUHII dynamics. Therefore, this study

provides important insights into urban climate research, risk mitigation strategies, and sustainable urban planning in the context of urbanization.

Section snippets

Study area and data set

Asia, the largest continent, has diverse landforms as well as a range of climate types, which provides an effective foundation for multi-source multi-temporal information fusion, and spatial differential extraction strategies. Additionally, extensive urban expansion has occurred over the past two decades (Sun et al., 2020). Extensive built-up areas provide diverse impervious surfaces, which are crucial for advancing methods in large-scale remote sensing mapping and urban thermal environment ...

Methods

A comprehensive method was developed for estimating DISP to assess the change of UHI effect, as shown in Fig. 1. This method consists of the following: (1) Obtaining time series samples of impervious surface percentage; (2) Constructing a feature set and prediction model to estimate regional time series impervious surface percentage; (3) Applying logical correction to the time series data based on the overall trend; (4) Analyzing trends and differences in SUHII. ...

Results of geographic zoning and seasonal periods

The results for the Asian subregion and the corresponding time windows are illustrated in Fig. 2. Asia was divided into seven subregions. Two distinct seasons were identified annually, namely high-growing and low-growing periods (Fig. 2b). Multi-seasonal features were used to obtain from MOD09A1 based on different periods. In most subregions, the high-growing period was mainly in the middle of each year, while the low-growing period primarily took place at the beginning and end of each year. ...

Comparison with other impervious surface products

To evaluate the feasibility and reliability of the proposed DISP framework, we conducted a comparative analysis with existing impervious surface products. This comparison aimed to assess the consistency, accuracy, and spatiotemporal representativeness of DISP. The impervious area in Asia from 2000 to 2023 is quantitatively assessed in Fig. 12. The total impervious area increased from $2.006 \times 10^5 \text{ km}^2$ to $4.108 \times 10^5 \text{ km}^2$, effectively doubling over the past two decades. We counted the area of DISP ...

Conclusions

There are differences in the changes and patterns of regional impervious surfaces at large scales, which affect the trend and distribution of UHI effects. However, previous frameworks cannot reflect the various complex changes of impervious surfaces during urbanization, and thus cannot effectively evaluate the degree of aggravation or alleviation of the UHI effect during urban renewal. To this end, we proposed a novel method for estimating the DISP to quantify the trend of SUHII under different ...

CRedit authorship contribution statement

Tianyu Xu: Writing – review & editing, Writing – original draft, Validation, Methodology. **Jie Gong:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Zhihui Yang:** Writing – review & editing. **Yixu Wang:** Investigation. **Tiantian Jin:** Visualization. **Imanmadi Duman:** Investigation. **Ermekov Farabi Kerimbaevich:** Visualization. ...

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. ...

Acknowledgments

The work was supported by the National Natural Science Foundation of China under Grant [42171090]; and Major project of the Ministry of Science and Higher Education of Kazakhstan under Grant [BR24993222]. ...

[Recommended articles](#)

References (78)

M.N. Ahmad *et al.*

[A novel ensemble learning approach to extract urban impervious surface based on machine learning algorithms using SAR and optical data](#)

International Journal of Applied Earth Observation and Geoinformation (2024)

J.F. Brown *et al.*

[Lessons learned implementing an operational continuous united states national land change monitoring capability: The land change monitoring, assessment, and projection \(LCMAP\) approach](#)

Remote Sensing of Environment (2020)

T. Chakraborty *et al.*

[A simplified urban-extent algorithm to characterize surface urban heat islands on a global scale and examine vegetation control on their spatiotemporal variability](#)

International Journal of Applied Earth Observation and Geoinformation (2019)

Y. Cui *et al.*

[AGTML: A novel approach to land cover classification by integrating automatic generation of training samples and machine learning algorithms on Google earth engine](#)

Ecological Indicators (2023)

H. Du *et al.*

[Weekly rhythms of urban heat islands: A multicity perspective](#)

Sustainable Cities and Society (2024)

Y. Dvornikov *et al.*

[Optimal spectral index and threshold applied to sentinel-2 data for extracting impervious surface: Verification across latitudes, growing seasons, approaches, and comparison to global datasets](#)

International Journal of Applied Earth Observation and Geoinformation (2023)

Z. Fang *et al.*

[Unveiling driving disparities between satisfaction and equity of ecosystem services in urbanized areas](#)

Resources, Environment and Sustainability (2024)

P. Gong *et al.*

[40-year \(1978–2017\) human settlement changes in China reflected by impervious surfaces from satellite remote sensing](#)

Science Bulletin (2019)

P. Gong *et al.*

[Annual maps of global artificial impervious area \(GAIA\) between 1985 and 2018](#)

Remote Sensing of Environment (2020)

S. Guan *et al.*

Mitigating urban heat island through urban-rural transition zone landscape configuration: Evaluation based on an interpretable ensemble machine learning framework

Sustainable Cities and Society (2025)



View more references

Cited by (0)

[View full text](#)

© 2025 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.



All content on this site: Copyright © 2025 Elsevier B.V., its licensors, and contributors. All rights are reserved, including those for text and data mining, AI training, and similar technologies. For all open access content, the relevant licensing terms apply.

