Tracing the Heat: LULC Changes and Urban Heat Island Dynamics in Abu Dhabi's Expanding Landscape

Basam Dahy [1], Yi Yin [2], Prashanth Marpu [3], Catherine Benedicta Nixon [4], Rita Sousa [5]

[1] Civil and Urban Engineering, New York University Abu Dhabi, PO Box 129188, Abu Dhabi, UAE - bsd9396@nyu.edu
[2] Department of Environmental Studies, New York University, 285 Mercer Street, NY 10012 - yi.yin@nyu.edu
[3] Bayanat, Al Maryah Island, PO Box 111143 Abu Dhabi, UAE - prashanth.marpu@space42.ai
[4] Civil Engineering, University of Wollong in Dubai, P.O. Box 2018, Dubai, UAE - cathynixon21@yahoo.com
[5] Civil and Urban Engineering, SHORES Center, New York University Abu Dhabi, PO Box 129188, Abu Dhabi, UAE - rita.sousa@nyu.edu

Keywords: Land Surface Temperature, Urban Expansion, Coastal Reclamation, Machine Learning, Remote Sensing, Arid Region.

Abstract

Urban Heat Island (UHI) effects in arid environments are influenced by urban expansion, land-use changes, and water body dynamics. This study provides an updated analysis of UHI trends in Abu Dhabi using Land Surface Temperature (LST) data retrieved from moderate-resolution Landsat imagery spanning from April 2013 to December 2024. Monthly and seasonal LST trends are assessed across four land-use categories: consistent urban, land to urban (developed), inundation, and reclamation. Results reveal that while urban areas exhibit a cooling trend in peak summer (-2.46°C/year), they show a significant warming trend in winter (+2.64°C/year), reinforcing UHI effects. Inundation zones demonstrate the oasis effect, mitigating peak summer heat (-2.37°C/year). At the same time, reclamation areas show sustained warming in both seasons (+2.93°C/year in summer, +4.20°C/year in winter), indicating the loss of natural heat-buffering mechanisms. A key novelty of this study is the integration of land cover and land-use change analysis with multi-seasonal LST trends, revealing the aggressive construction-driven transformation of the urban landscape. Unlike previous studies (e.g., Lazzarini et al., 2015), which primarily documented UHI presence, our research highlights how changes in land-use composition, particularly the loss of water bodies and green spaces due to reclamation, exacerbate warming trends despite urban cooling interventions. The findings challenge earlier assumptions of a uniform UHI increase, showing that land-use planning plays a decisive role in seasonal heat retention and dissipation. However, ongoing land reclamation appears to counteract these gains, necessitating further research on climate adaptation strategies.

1. Introduction

Urban Heat Island (UHI) effects, where urban areas exhibit higher temperatures than their rural surroundings, are critical in arid regions like Abu Dhabi. UHI effects can exacerbate thermal discomfort and increase energy consumption in hot climates, with significant implications for urban sustainability (Santamouris, 2015). While many cities experience consistent urban warming, Abu Dhabi's distinctive urban design—integrating green infrastructure and water bodies—has led to the unique phenomenon of daytime cooling inversion in specific urban zones. Rapid urbanization, including large-scale projects and re-vegetation initiatives, has altered Land Use Land Cover (LULC), demanding a fresh analysis of how these changes influence surface temperatures (Lazzarini et al., 2015; Abulibdeh, 2021). This study aims to produce LULC maps for a series of key temporal years dataset for Abu Dhabi using Landsat imagery and advanced machine learning techniques. By correlating these maps with Land Surface Temperature (LST) data, the research provides critical insights into UHI dynamics and sustainable urban planning in Abu Dhabi and similar arid regions.

2. Study Area

The Emirate of Abu Dhabi, situated on the southern shore of the Arabian Gulf, covers an area of 67,340 km², making up more than 75% of the total area of the UAE. It features a diverse geography that encompasses both coastal and inland regions (Figure 1). This diversity underpins the focus of this study, which examines key land use patterns and environmental features across the emirate. Notable elements include the Dhafra Solar Plant in the south, the Ras Ghanada Marine Protected Area in the north, and various urban developments on the mainland, such as Al Maqta, Musaffah, Mohamed Bin Zayed City, Khalifa City, Masdar City, Al Raha Beach, Shakhbout City, and Bani Yas. With a hot desert climate, the region experiences summer (April-September) temperatures exceeding 40°C, frequent sandstorms, and dense fog during cooler months with temperature ranging from 10 to 24°C (October-March). These climatic and geographical characteristics, coupled with the rapid pace of urbanization, make Abu Dhabi an ideal location for analyzing LULC changes and UHI dynamics.

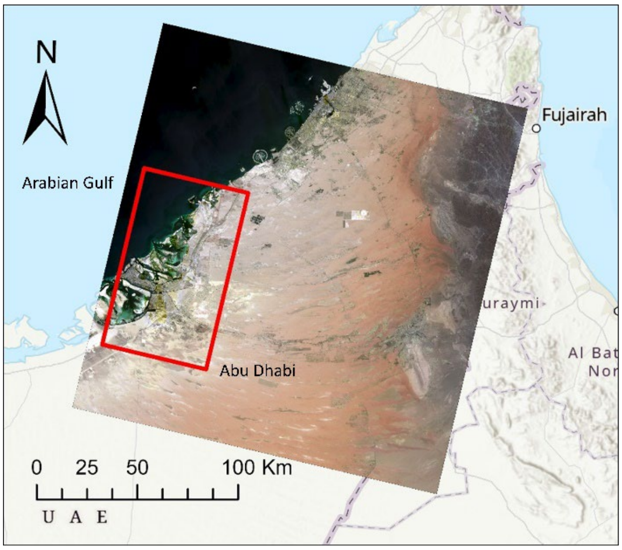

Figure 1. Study area on Landsat 160/43 over Abu Dhabi.

3. Methods

3.1 Data Sources, Preprocessing, and Processing

To analyze LULC changes since the country's independence in 1971 and the subsequent development driven by oil production revenue, thematic maps were generated for the past five decades. These maps were created using 10 key temporal datasets (1972, 1986, 1992, 1997, 2002, 2008, 2013, 2017, 2021, and 2024) derived from Landsat MSS, TM, ETM+, and OLI imagery (Table 1). Additionally, a continuous time-series analysis was conducted in Google Earth Engine (GEE) to capture gradual LST monthly changes from April 2013 to December 2024.

Sensor	Year	Bands	Resolution
OLI	26/09/2024, 10/09/2021, 15/09/2017, 18/07/2013	B3-Green, B4-Red, B5-NIR, B6-SWIR1 B8-Panchromatic B10-Thermal IR	30 m 30 m 30 m 30 m 15 m 100 m
ETM+	30/09/2002	B2-Green, B3-Red, B4-NIR, B5-SWIR1 B8-Panchromatic	30 m 30 m 30 m 30 m 15 m
TM	17/05/2008, 24/09/1997, 10/9/1992, 13/11/1986	B2-Green, B3-Red, B4-NIR, B5-SWIR1	30 m 30 m 30 m 30 m
MSS	29/11/1972	B4-Green, B5-Red, B6-NIR1, B7-NIR2	60 m 60 m 60 m 60 m

Table 1. Landsat spectral bands used in this study.

Pre-processing included band stacking, pan-sharpening with the Hyperspectral Color Space method, and resampling all datasets to a consistent 15m resolution. To enhance classification accuracy, four spectral indices were computed to differentiate vegetation, urban areas, water bodies, and bare soil: 1.Normalized Difference Vegetation Index (NDVI), which is effective in differentiating vegetation from other land cover classes; 2.Normalized Difference Built-up Index (NDBI), which is used to highlight urban and built-up areas; 3.Modified Normalized Difference Water Index (MNDWI), which enhances the detection of water bodies in urban and arid regions; and 4. Dry Bare-Soil Index (DBSI), which differentiates barren land from other classes (Rasul et al., 2018). To further improve classification accuracy, compactness layers—which represent object shape attributes based on the ratio of an object’s perimeter to that of a circle with the same area—were generated and integrated alongside spectral and spatial attributes.

The Random Forest (RF) classifier was selected for its superior performance and trained using these attributes to produce thematic maps of four LULC classes: desert, urban, vegetation, and water (Sultan et al., 2024; Dahy et al., 2022). Training samples accounted for 80% of the dataset, while 20% were reserved for accuracy assessment using confusion matrices. LULC classification was performed using the RF classifier, which demonstrated high accuracy in distinguishing urban and desert land types. The model incorporated single Landsat bands (green, red, IR, SWIR1), spectral indices, and compactness layers, enhancing classification performance. The overall accuracies of the LULC maps were 93.6%, 91.7%, 95%, and 94.4% for the years 2024, 2013, 2002, and 1992, respectively (See Figure 2 in the Results section).

3.2 LULC Change Detection

After generating the LULC thematic maps, change detection analysis was conducted to examine spatio-temporal transformations in LULC across the study area. Change detection maps were produced by comparing LULC datasets from nine intervals (1972-1986, 1986-1992, 1992-1997, 1997-2002, 2002-2008, 2008-2013, 2013-2017, 2017-2021, 2021-2024) temporal periods. The analysis focused on identifying urbanized, reclaimed, and inundated areas over time. Urbanized areas included regions that transitioned into built-up environments, while reclaimed areas represented land recovered from water bodies, such as the construction of artificial islands. Inundated areas were defined as regions affected by flooding or water encroachment due to environmental factors or anthropogenic interventions, including the excavation of water channels. To quantify these changes, statistical analyses were performed to assess temporal trends in LULC transformations. The methodology involved generating thematic maps to illustrate land reclamation versus inundation and urban expansion across multiple time intervals. Distinct colors were used to differentiate changes across the nine intervals, enabling a clear visualization of spatial and temporal dynamics. Time-series data were then analyzed to extract quantitative statistics on both types of transitions—land reclamation versus inundation and urban expansion. The resulting statistics were visualized through bar charts and time-series graphs, providing a detailed representation of the magnitude and rate of change for each period.

3.3 LST Extraction, Analysis, and Heat Tracing

LST layers for the study area were derived using GEE with Landsat 8 OLI/TIRS thermal data from April 2013 to December 2024. Thermal infrared data for LST retrieval in GEE has been available from Landsat 8 OLI/TIRS since 2013. The analysis involved defining the area of interest (AOI), filtering Landsat 8 surface temperature data for low-cloud coverage (<20%), and applying a custom cloud-masking function to eliminate atmospheric distortions. LST values were computed from thermal band 10 using Landsat scale factors, converting digital numbers (DN) to surface temperature in degrees Celsius using the following equation:

$$\mathrm{LST}(^{\circ}\mathrm{C}) = \mathrm{DN} \times 0.00341802 + 149 - 273.15 \quad (1)$$

Where DN represents the digital number of the band 10 pixels.

A total of 141 monthly LST layers were retrieved from GEE platform for the study period April 2013 to December 2024. These layers were clipped to the AOIa and subsequently downloaded for further analysis using ERDAS Imagine 2023 and ArcGIS Pro. A sampling approach was implemented to investigate the relationship between LST variations and LULC transformations. Polygons were manually digitized with clearly defined boundaries to classify four distinct land cover transition types: (a) consistent urban areas, (b) non-urban to urban conversion, (c) non-water to water (inundation), and (d) water to non-water (reclamation). For each category, 10 sample sites were carefully selected to ensure representative spatial coverage. At each site, mean DN values were extracted from the LST layers, and the average LST value for each category was computed as the mean of the 10 sample means, with the standard error used to quantify variability. To illustrate spatio-temporal LST changes, an LST change map was produced, categorizing pixels into

https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-339-2025 | © Author(s) 2025. CC BY 4.0 License.

increase, decrease, or no significant change zones. Additionally, a time-series analysis was conducted to track LST fluctuations within each category, enabling an assessment of the relationships between LST variations and LULC changes. This analysis provides insights into the thermal impacts of urbanization, land reclamation, and inundation processes.

4. Results

4.1 LULC Changes Over Time

The LULC analysis reveals substantial land transformations in Abu Dhabi between 1972 and 2024, driven by rapid urbanization, coastal reclamation, and land inundation (Figure 2). These changes reflect major developmental phases, including urban expansion, industrial growth, large-scale greening initiatives, and the creation of artificial islands.

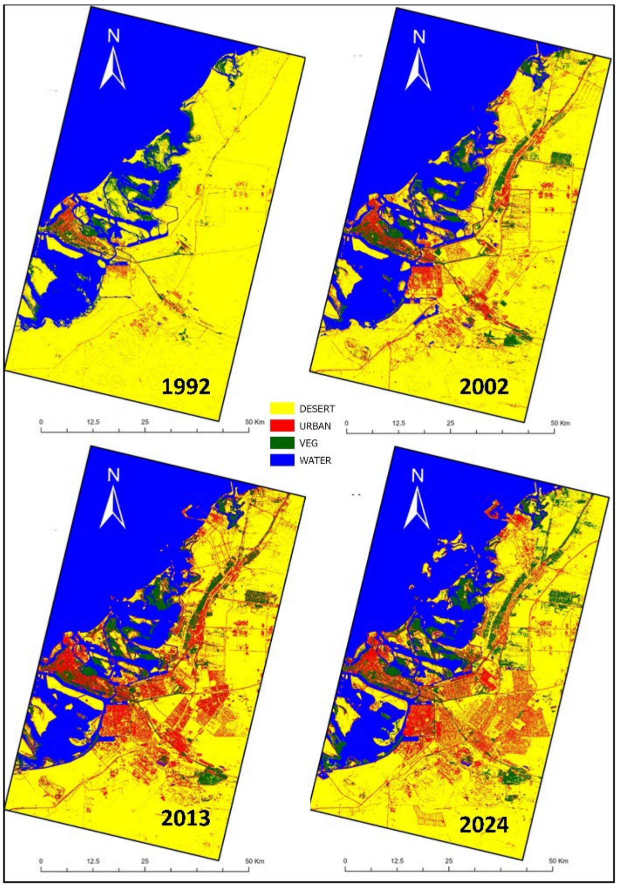

Figure 2. LULC maps of Abu Dhabi for 1992, 2002, 2013, and 2024, highlighting urban expansion, vegetation shifts, and coastal changes.

4.1.1 Urbanization Trend: Urban expansion in Abu Dhabi has been substantial over the past five decades, with a total increase of 624.2 km² in urban areas between 1972 and 2024 (Figure 3). However, the rate of urbanization has varied across different time intervals (Figure 4). The most rapid urban expansion occurred between 2008 and 2013, with an increase of 434.7 km², coinciding with large-scale infrastructure and economic development projects. Other significant growth periods include 1992–1997 (300.8 km²) and 2013–2017 (313.8 km²). Conversely, the slowest urban expansion was observed between 1986 and 1992, with an increase of only 73.8 km², potentially reflecting economic or policy-driven slowdowns in urban development.

4.1.2 Coastal Reclamation and Inundation Trends: Beyond urban expansion, Abu Dhabi has also undergone significant coastal land transformations through reclamation and inundation processes. A total of 224.22 km² of land has been reclaimed from coastal areas since 1972, while 55.91 km² has been lost to inundation (Figure 5, Figure 6, and Figure 7), primarily driven by the development of artificial islands and waterfront expansion projects. Another notable reclamation surge was observed between 2002 and 2008, where 83.94 km² of land was reclaimed within just six years, marking one of the most rapid coastal expansions during the study period. This phase coincided with intensified coastal development efforts, including large-scale urban waterfront projects and offshore infrastructure expansion. However, reclamation rates declined after 2013, with the lowest recorded value between 2013 and 2017 (18.45 km²). Despite this decline, 18.45 km² still represents a considerable amount of coastal reclamation within just four years, highlighting the continued expansion of reclaimed land in Abu Dhabi.

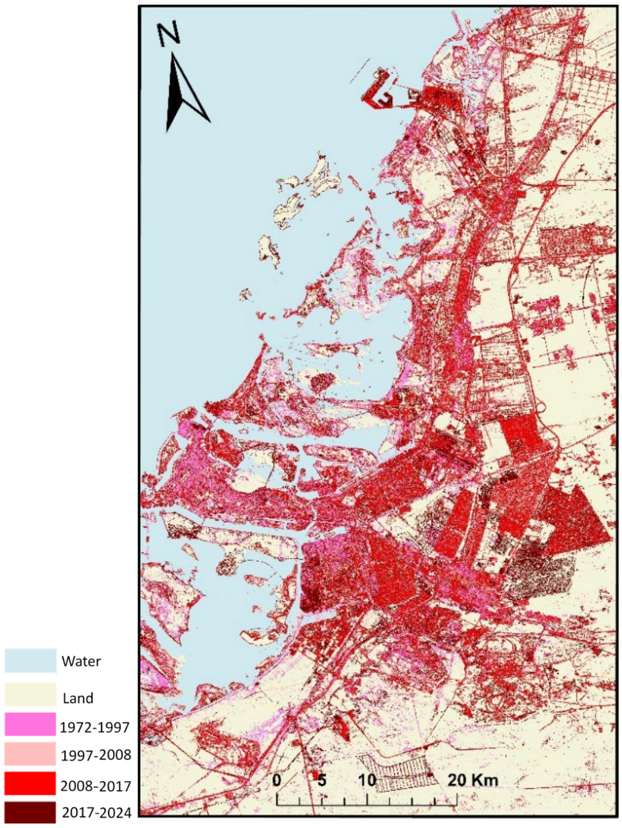

Figure 3. Urbanization changes in Abu Dhabi (1972–2024).

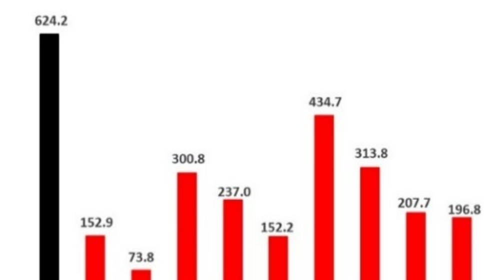

Figure 4. Time-series of urbanization changes in Abu Dhabi from 1972 to 2024 (in km^2).

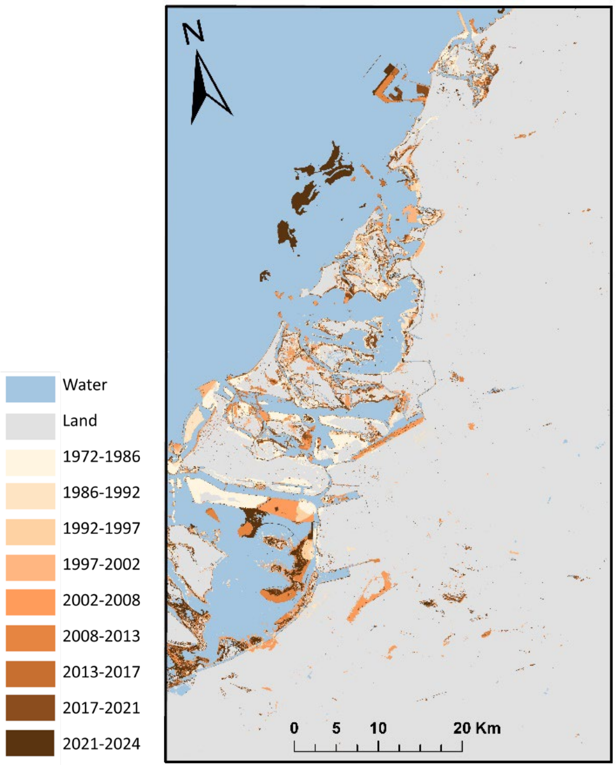

Figure 5. Coastal reclamation changes in Abu Dhabi across nine Intervals (1972–2024).

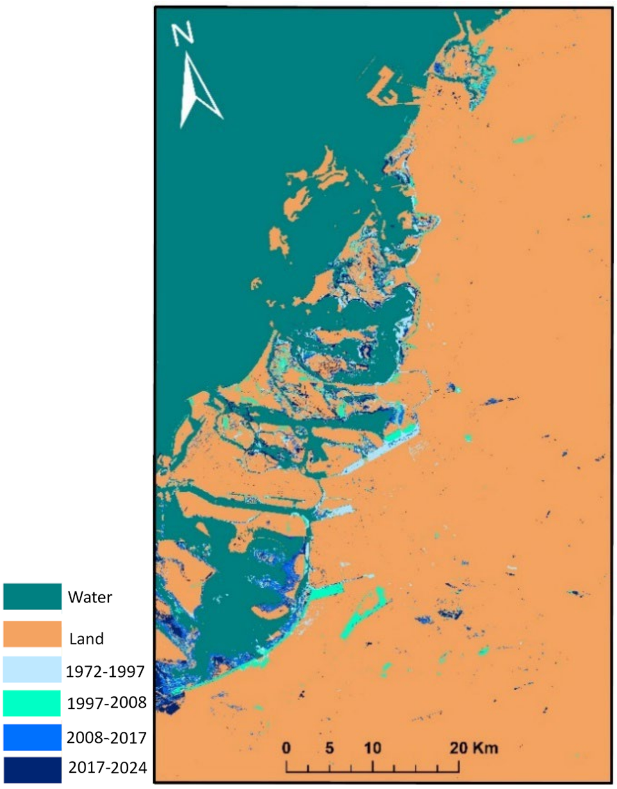

Figure 6. Inundation changes in Abu Dhabi (1972–2024).

Conversely, land inundation exhibited a fluctuating trend over time (Figure 6 and Figure 7). The highest inundation rate was recorded between 1992 and 1997 (71.57 km²), potentially due to coastal erosion, sea-level rise, or human-induced hydrological changes. Other significant inundation periods include 1997–2002 (54.95 km²) and 2008–2013 (45.87 km²).

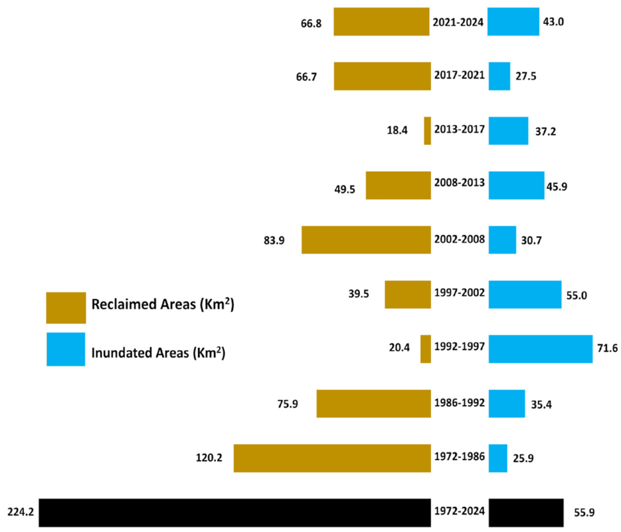

Figure 7. Time series of changes in reclaimed and inundated areas of Abu Dhabi from 1972 to 2024 (in km²).

4.2 LST Variations and Heat Mapping

The analysis of 141 monthly LST layers from April 2013 to December 2024 reveals significant spatio-temporal variations in land surface temperature across different land cover transitions. A LST change map (2024 minus 2013) was generated to highlight areas of temperature increase, decrease, and stability, with light shade indicating warming trends, dark shade representing cooling areas, and medium gray showing minimal or no change (Figure 8). To further understand the relationship between LST variations and LULC changes, 40 sample polygons were manually digitized and classified into four LULC transition categories (see 3.3. subsection): (a) consistent urban (areas that remained urban throughout the study period), (b) non-urban to urban (newly developed urban areas), (c) non-water to water (inundation, land converted to water bodies), and (d) water to non-water (reclamation, land reclaimed from water bodies).

4.2.1 Monthly LST Trends Across LULC Categories: Distinct LST patterns were observed in the four categories, with notable seasonal fluctuations and long-term trends influenced by land-use transitions.

Consistent urban areas exhibited elevated average LST values throughout the study period, with peak summer temperatures (July) reaching ~50.9°C and winter lows (January) dropping to ~28°C (Figure 9). These seasonal fluctuations are indicative of the UHI effect, where urban materials such as asphalt and concrete retain heat, reducing nighttime cooling. The overall long-term warming trend was minimal (+0.018°C/year, $p=0.93$), indicating statistical insignificance (Figure 10). The seasonal trends (Summer – June, July, August - and Winter – December, January and February) are also slightly positive but not statistically significant.

Areas that transitioned from non-urban to urban exhibited a slight increase in LST post-conversion, but the trend remains statistically insignificant. The average LST for the entire study period (141 months) was 40.7°C. When dividing the data into two distinct periods, the pre-conversion period (approx. 70 months) had an average LST of 40.8°C, while the post-conversion period showed an average LST of 41.2°C. The highest recorded LST in 2024 reached 41.6°C, suggesting a measurable rise over time.

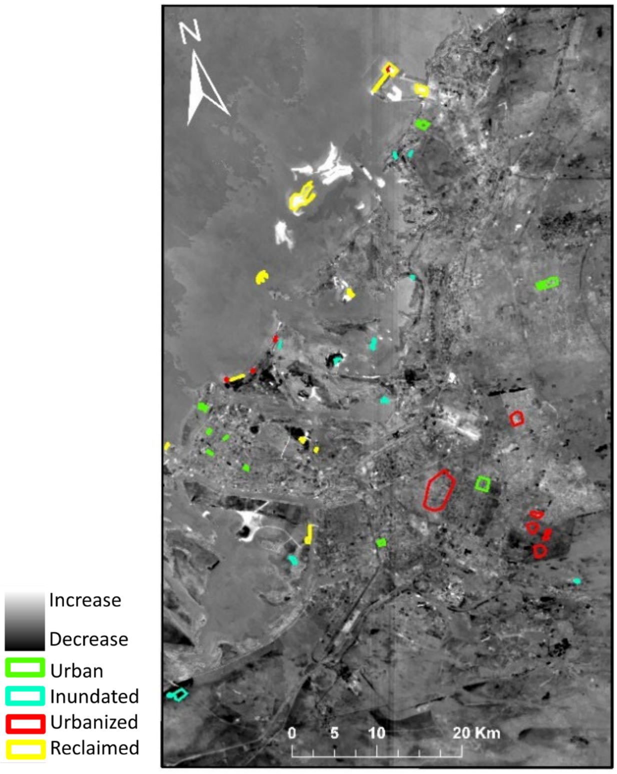

Figure 8. LST change map (2013–2024), highlighting temperature increase (light shade), decrease (dark shade), and stability (medium gray), overlaid with 40 polygons representing sample areas for each LULC transition category.

Seasonal trends provide additional insight into how temperature fluctuations evolved in post-conversion. While peak summer temperatures increased (+0.26°C/year), and winter lows also showed a slight upward trend (+0.29°C/year), neither trend is statistically significant.

Inundated areas, such as new water channels and flood zones, exhibited a general cooling trend, reinforcing the thermal buffering role of water bodies. The overall cooling rate was -0.14°C/year, though this trend was not statistically significant. However, seasonal trends provide stronger evidence of water-driven temperature regulation:

- Peak summer cooling (-0.15°C/year): A statistically significant cooling effect, indicating that water bodies effectively mitigate extreme summer heat through evaporative cooling.

- Winter temperature increase (+0.178°C/year): A statistically significant warming trend over time, likely driven by the thermal inertia of water bodies, which retain heat absorbed during warmer months and release it during winter. Additionally, reduced seasonal cooling due to landscape or climate changes may have contributed to this warming trend.

These findings reinforce the "oasis effect," where water bodies act as thermal stabilizers, reducing temperature extremes and contributing to localized climate regulation.

Reclaimed areas exhibited a distinct warming pattern, particularly during peak summer months, highlighting the long-term impact of land modification. The overall warming trend suggests that these areas are increasingly absorbing and retaining heat over time, with seasonal variations providing deeper insight into this trend:

- Peak summer warming (+0.384°C/year): Reclaimed areas experienced a strong and statistically significant increase in peak summer temperatures. This trend suggests that newly developed surfaces, which likely replaced water bodies or vegetated land, are intensifying heat accumulation during the hottest months. The lack of natural cooling mechanisms, such as water evaporation or shading, may be contributing to this rise in temperature.

- Winter low warming (+0.305°C/year, the highest warming trend among all categories): Reflects the amplified heat retention capacity of artificial land post-reclamation. These results emphasize the thermal cost of land reclamation, where natural cooling mechanisms are replaced with heat-retaining surfaces, exacerbating local heat stress.

Seasonal Temperature Profile: 1. Average summer temperature: 38.04°C; 2. Average winter temperature: 23.64°C. This confirms that reclaimed areas remain cooler than consistent urban environments but are steadily warming, likely due to ongoing land transformation activities.

5. Discussion

The findings of this study reveal significant insights into the dynamics of LST trends across four LULC categories in Abu Dhabi over the 2013–2024 period. While some global trends were statistically insignificant, seasonal trends provided crucial evidence of thermal variability driven by land-use changes and climatic conditions.

<u>Consistent urban areas</u> exhibited strong seasonal fluctuations, with elevated summer temperatures and significant winter warming. The gradual cooling trend during peak summer (-2.46°C/year) suggests the potential effectiveness of urban cooling measures, such as increased vegetation cover and reflective surfaces. However, persistent winter warming (+2.64°C/year) highlights the challenges of heat retention in cooler months, exacerbating UHI effects. These observations underscore the dual challenge of mitigating seasonal extremes in urban areas. <u>Urbanized areas</u> transitioning from non-urban to urban demonstrated amplified seasonal contrasts post-conversion. While the global warming trend was statistically insignificant, significant cooling during summer (-2.66°C/year) and marginal winter warming (+2.38°C/year) reflect the thermal impacts of impervious surfaces replacing natural vegetation. Seasonal variations became more pronounced, indicating how urbanization intensifies thermal behavior. <u>Inundated areas</u> showed a clear cooling trend, particularly during summer (-2.37°C/year), attributed to the oasis effect, where water bodies in mitigating temperature extremes and maintaining local microclimates. <u>Reclaimed areas</u> demonstrated the strongest warming trends, both in summer (+2.93°C/year) and winter (+4.20°C/year). The replacement of water with heat-retaining artificial surfaces drove consistent temperature increases, amplifying seasonal fluctuations and exacerbating local heat stress. These results highlight the long-term thermal costs of reclamation activities and the need for sustainable reclamation practices.

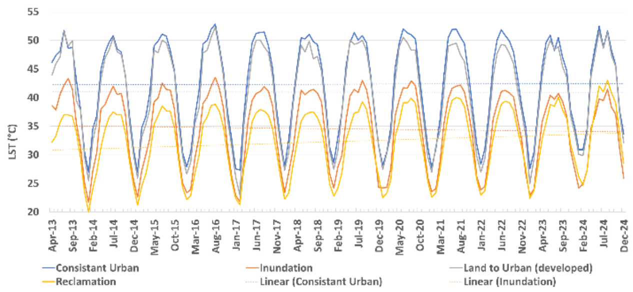

Figure 9. Long-term trends in LST.

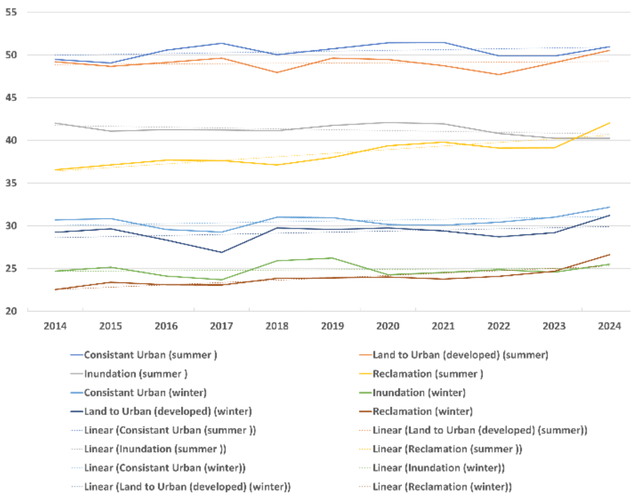

Figure 10. Corrected seasonal trends: peak (July) Vs. low (January) LSTs.

Overall, this study reveals that while mitigation strategies, such as increased vegetation cover, artificial shading, reflective surfaces, and the preservation or creation of water bodies, may stabilize summer temperatures in urban and urbanized areas, winter warming remains a critical challenge. The oasis effect in inundated zones underscores the importance of water bodies, while the warming in reclaimed areas highlights the detrimental effects of land-use transitions on local climates.

6. Conclusions and Future Work

This study provides a comprehensive analysis of LST trends in Abu Dhabi, emphasizing the interplay between land-use transitions, seasonal dynamics, and long-term thermal behavior.

Key conclusions include:

1. UHI dynamics: Consistent urban and urbanized areas exhibit cooling during summer but retain significant heat during winter, reinforcing persistent UHI effects.

2. Impact of urbanization: Transitioning land to urban use amplifies seasonal temperature contrasts, with stronger summer peaks and winter heat retention.

3. Oasis effect: Inundated areas demonstrate the critical role of water bodies in mitigating extreme summer heat and stabilizing local temperatures.

4. Thermal cost of reclamation: Reclaimed areas show consistent warming due to the loss of water's natural cooling influence and the introduction of heat-retaining land surfaces.

Even though the findings are robust, the study is subject to certain limitations. The analysis was based on a relatively small sample size, with only 10 samples per LULC category. This limited dataset may reduce the statistical power of some trends and highlight the need for broader spatial coverage in future studies. Additionally, the reliance on satellite-derived LST data, while useful, necessitates validation through field-based measurements to ensure accuracy and reliability.

These results represent preliminary findings from the ongoing "***Climate Under Construction***" project, which seeks to provide a more detailed understanding of UHI effects and land-use transitions in arid environments. Future work will focus on expanding the dataset, incorporating field measurements to validate remote sensing results, and leveraging machine learning models to refine the analysis of seasonal temperature variations.

Funding: This research was supported by the 19WSN Faculty Fellowship (Grant No. 75-71003-ADHPG-SQN01), from New York University Abu Dhabi (NYUAD).

References

Lazzarini, M., Molini, A., Marpu, P.R., Ouarda, T.B., Ghedira, H., 2015: Urban climate modifications in hot desert cities: The role of land cover, local climate, and seasonality. *Geophysical Research Letters*, 42(22), 9980-9989. doi.org/10.1002/2015GL066534.

Santamouris, M. (2015). Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Science of the Total Environment, 512-513*, 582-598. doi.org/10.1016/j.scitotenv.2015.01.060

Abulibdeh, A., 2021: Analysis of urban heat island characteristics and mitigation strategies for eight arid and semi-arid Gulf region cities. *Environmental Earth Sciences,* 80(259). doi.org/10.1080/19427867.2020.1857908.

Rasul, A., Balzter, H., Ibrahim, G. R. F., Hameed, H. M., Wheeler, J., Adamu, B., Najmaddin, P. M., 2018: Applying built-up and bare-soil indices from Landsat 8 to cities in dry climates. *Land,* 7(3), 81. doi.org/10.3390/land7030081.

Sultan, M., Issa, S., Dahy, B., Saleous, N., Sami, M., 2024: Fifty years of land use and land cover mapping in the United Arab Emirates: A machine learning approach using Landsat satellite data. *Frontiers in Earth Science, 12.* doi.org/10.3389/feart.2024.1510510.

Dahy, B., Issa, S., Saleous, N., 2022: Random forest for classifying and monitoring 50 years of vegetation dynamics in three desert cities of the UAE. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 43, 69-76. doi.org/10.5194/isprs-archives-XLIII-B3-2022-69-2022.

Lazzarini, M., Marpu, P. R., Ghedira, H., 2013: Temperature-land cover interactions: The inversion of urban heat island phenomenon in desert city areas. *Remote Sensing of Environment,* 130, 136–152. doi.org/10.1016/j.rse.2012.11.007.