Evaluating Human-Induced Changes in Land Surface Temperature in the Southern Caspian Sea Area: The Case of Anzali Free Zone Development

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Abstract

Human-induced land use and land cover changes significantly influence the Earth's surface temperature, especially in rapidly developing regions. This study investigates the impact of urban development associated with the Anzali Free Zone Organization, located along the southern coast of the Caspian Sea, on land surface temperature (LST) changes over a 24-year period (2000–2024). Multitemporal Landsat ETM+ and OLI satellite imagery were employed to analyze spatial and temporal variations in surface temperature. Following radiometric, atmospheric, and reflectance corrections, the Normalized Difference Vegetation Index (NDVI) was calculated to derive vegetation fraction (PV), which in turn was used to estimate surface emissivity. Brightness temperature was then computed using thermal bands, and LST was derived via the single-channel algorithm. The results indicate a significant alteration in LST, ranging from 16.5°C to 41.7°C in 2000 and from 20.1°C to 37.3°C in 2024. These temperature variations correlate strongly with reduced vegetation cover and the expansion of impervious surfaces driven by increased housing demand, trade, and tourism in the Free Zone. The findings demonstrate a clear manifestation of the Urban Heat Island (UHI) effect, underscoring the ecological consequences of unchecked urbanization. This study highlights the need for sustainable land use planning and vegetation conservation strategies to mitigate thermal stress and preserve environmental integrity in coastal urban areas.

1. Introduction

Human activities have become a dominant force driving environmental change across the globe. Among the most critical consequences of anthropogenic influence is land use and land cover change (LUCC), which directly alters ecological processes, climate dynamics, and surface energy balance (Mostafa et al., 2023). These impacts are particularly acute in developing countries, where rapid urbanization often proceeds without comprehensive environmental planning (Chen et al., 2016).

According to the United Nations, the global urban population is projected to rise from 3.9 billion in 2014 to approximately 6.4 billion by 2050, highlighting a dramatic shift from rural to urban living patterns (UN, 2014). This transition is closely tied to changes in agricultural and natural landscapes, with increasing encroachment of built-up areas replacing vegetation and open land. Such transformation not only fragments ecosystems but also disrupts local climatic conditions. In response, remote sensing technologies have emerged as essential tools for monitoring urban expansion and environmental degradation (Araya & Cabral, 2010).

Urban sprawl, characterized by uncontrolled growth of residential, commercial, and infrastructural development, plays a significant role in altering land surface temperature (LST). The conversion of permeable, vegetated land to impervious surfaces such as concrete and asphalt modifies the thermal properties of the landscape, reducing evapotranspiration and increasing heat retention. These processes contribute to the Urban Heat Island (UHI) effect, where urban centers exhibit significantly higher temperatures than surrounding rural areas (Imran et al., 2021; Zoghi et al., 2023).

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LST is largely governed by the absorption and emission of solar radiation. Urban construction materials, due to their high thermal conductivity and low albedo, intensify surface warming (John et al., 2020). Additionally, the reduction in vegetation—often replaced by buildings and paved surfaces—diminishes local humidity and latent heat flux, further escalating surface temperatures (Igun & Williams, 2018; Pordel et al., 2017).

This feedback loop is exacerbated by rising demand for housing, food production, and transportation infrastructure, particularly in economically strategic regions. As vegetation loss continues, essential ecosystem services such as carbon sequestration, soil moisture regulation, and erosion control are jeopardized (Nzoiwu et al., 2017). Moreover, LUCC influences atmospheric processes by altering albedo, surface roughness, and evapotranspiration patterns, all of which have implications for regional climate and human thermal comfort (Purwanto & Kurniawan, 2016; Zhang & Liang, 2018).

Ultimately, the formation of localized microclimates due to land surface transformation is contributing to increased thermal stress in urban areas (Voogt & Oke, 2003). These trends underscore the urgency of assessing LST changes in rapidly developing coastal regions, where environmental sensitivity and urban pressure converge.

In this study, we utilized satellite data processing to analyze long-term land surface temperature changes resulting from land use alterations driven by human activities. Furthermore, we examined the relationship between the consequences of economic development and environmental changes along the southern coast of the Caspian Sea, a region that has been rarely investigated using the present approach.

2. Materials and Methods

2.1 Study Area

The Anzali Free Zone encompasses approximately 3,200 ha along the southern Caspian coastline (37° 25′–37° 27′ N, 49° 33′–49° 44′ E). The area under analysis spans roughly 225 km², including the port and adjacent coastal and inland zones (Figure 1). This region has undergone marked urban expansion due to the development activities led by the Free Zone Organization.

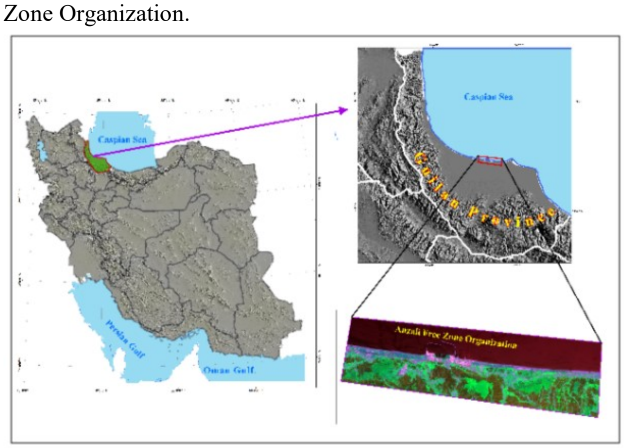

Figure 1. Location map of the study area in Iran.

2.2 Data Sources

Multi-temporal satellite imagery from Landsat 7 ETM+ and Landsat 8 OLI, each at 30 m spatial resolution, were obtained for the years 2000 and 2024 from the USGS repository (Chatrsimab et al., 2020a; 2020b). These datasets provide essential thermal and spectral bands required for deriving vegetation and surface temperature metrics.

2.3 Methodology

The workflow to derive Land Surface Temperature (LST) involved several steps (Figure 2):

Radiometric and Atmospheric Preprocessing: Digital numbers (DN) were converted to top-of-atmosphere radiance and reflectance. Atmospheric effects were corrected using the FLAASH radiative transfer model for both temporal datasets.

Vegetation Assessment: NDVI was computed for each scene, and vegetation proportion (PV) was extracted. Surface emissivity estimations leveraged NDVI-to-ε empirical relationships.

Thermal Conversion: Brightness temperatures (BT) were calculated using thermal bands (Band 6 for ETM+, Band 10 for OLI), following sensor-specific calibration and Planck's law.

LST Estimation: The single-channel algorithm incorporated BT and emissivity (ε) to derive LST maps for 2000 and 2024.

This methodological framework ensures consistent, spatiotemporal comparison across the study periods.

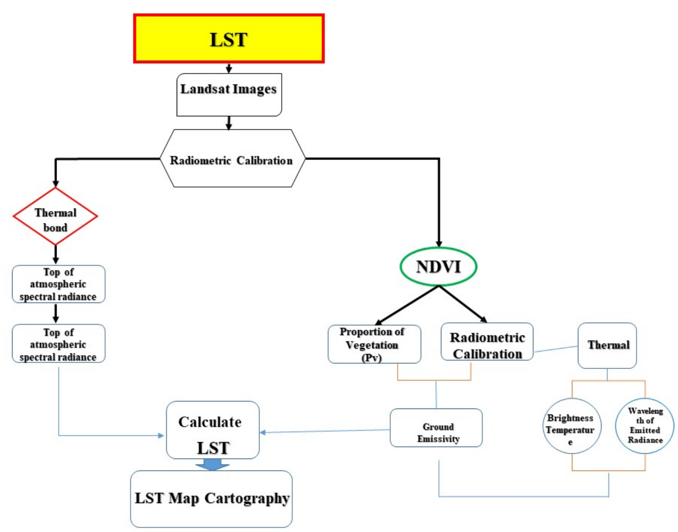

Figure 2. Flowchart

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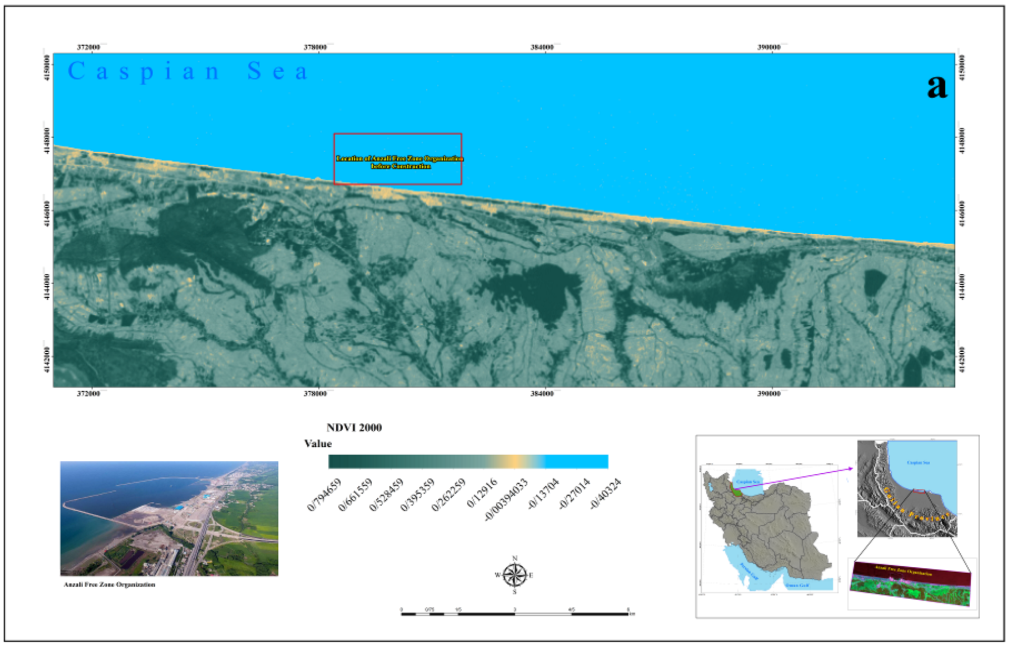
3. Results

The LST analysis revealed a notable thermal shift between 2000 and 2024:

- **2000:** Surface temperatures ranged from 16.5 °C to 41.7 °C.
- **2024:** The recorded range was 20.1 °C to 37.3 °C.

NDVI maps for 2000 and 2024 (Figures 3) demonstrate a substantial decline in vegetation cover and density, closely aligned with the emergence and intensification of thermal hotspots in transformed zones. These hotspots, particularly prominent around newly constructed infrastructure, reflect the thermal signature of impervious urban surfaces such as concrete and buildings (Figures 3,4). Figure 5 additionally illustrates the temporal shifts in both minimum and maximum values of NDVI and LST.



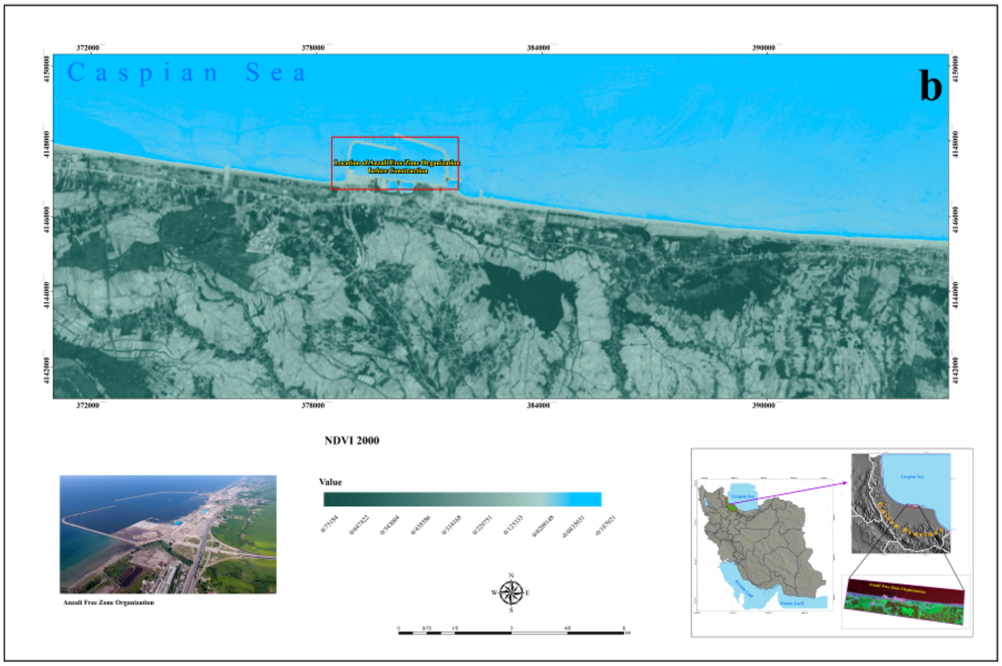
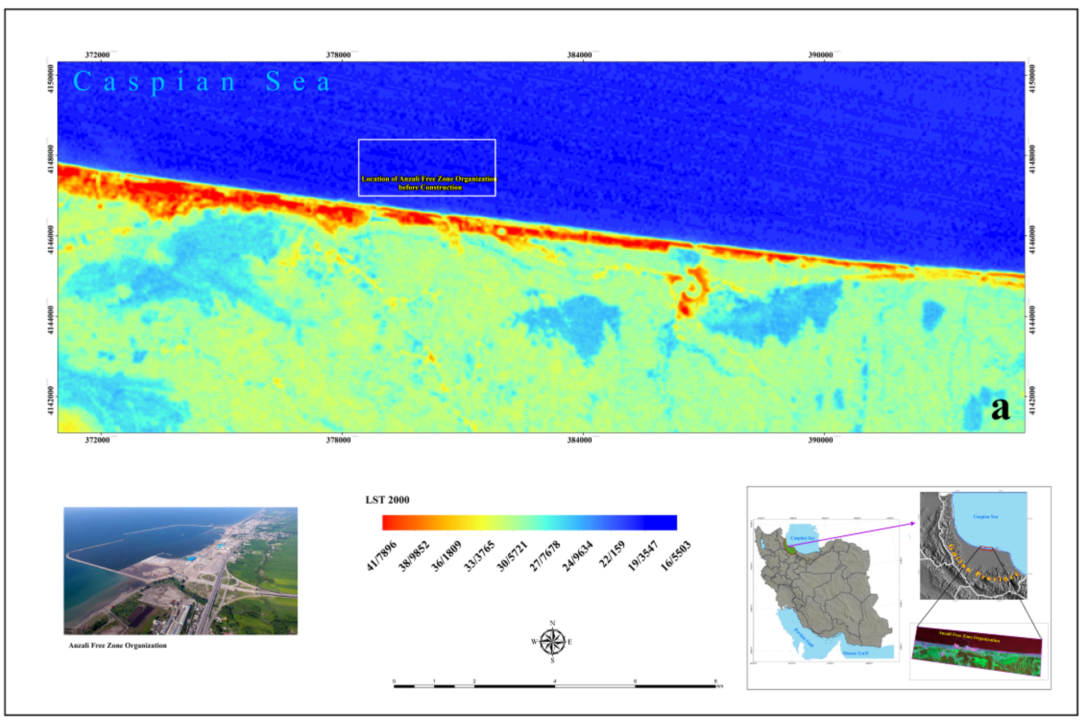


Figure 3. a and b: NDVI 2000, 2024



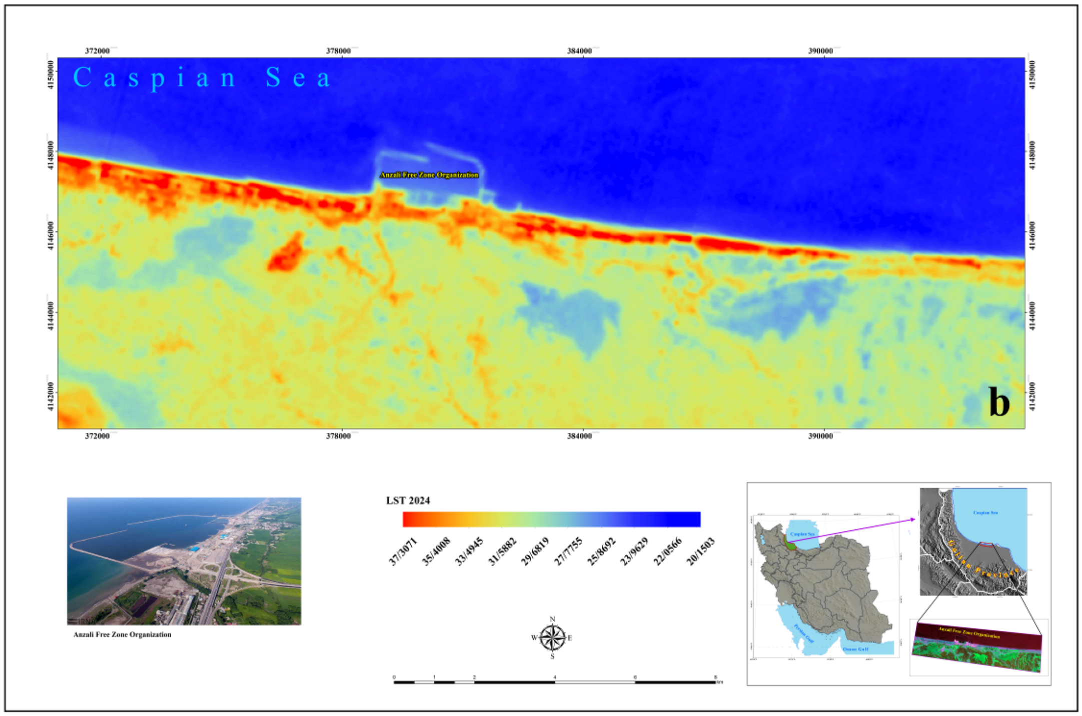


Figure 4. a and b: LST 2000, 2024

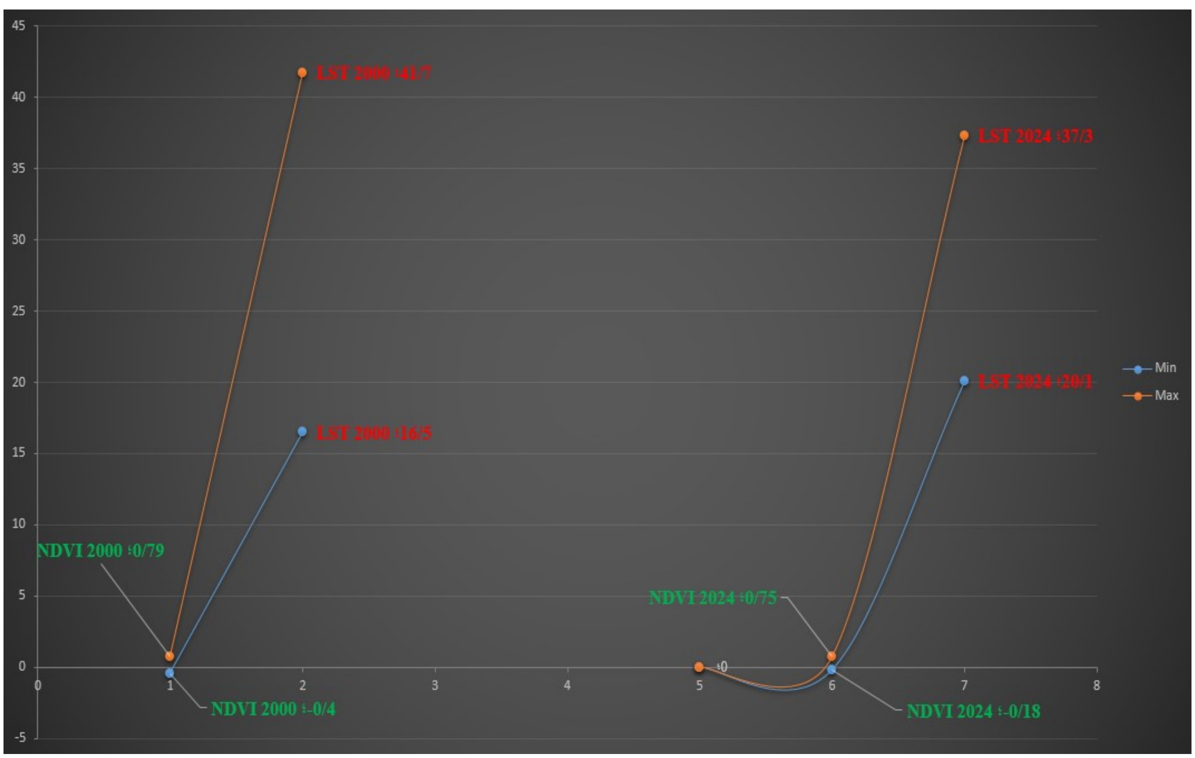


Figure 5. Minimum and maximum NDVI and LST.

4. Discussion and Conclusion

This study confirms that urban expansion in the Anzali Free Zone—driven by infrastructure development, tourism, and second-home ownership—has led to a substantial increase in land surface temperature (LST) over the past two decades. The conversion of vegetated land into impervious surfaces has reduced cooling through evapotranspiration, intensifying the Urban Heat Island (UHI) effect. These findings align with global studies (Weng, 2009; Fonseka et al., 2019), which show similar relationships between vegetation loss and thermal rise. Moreover, the lack of sufficient green infrastructure, as emphasized by Li et al. (2023), exacerbates thermal vulnerability in coastal cities. Spatial analysis confirms that zones with NDVI decline also exhibit the most significant LST increases. These results highlight the need for environmentally informed urban planning, including the integration of green spaces, thermal zoning, and sustainable land-use policies to mitigate rising surface temperatures and enhance resilience in the Caspian coastal region.

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