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Assessing Spatiotemporal Thermal Dynamics and Aridity Patterns through Multi-Sensor Remote Sensing Integration

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Abstract

This study introduces a versatile framework for tracking how heat and dryness change over time and space by combining various satellite data sources within Google Earth Engine. Using high-resolution MODIS temperature records from 2024, we examined Land Surface Temperature (LST) trends after filtering out low-quality data from both day and night readings to maintain accuracy. To better understand how the landscape holds onto energy and moisture, we measured thermal intensity through the daily temperature swing (ΔLST). In tandem, we used 2020 surface reflectance data to calculate the Solar-Based Aridity Index (SBAI). This process required cleaning the data of cloud interference and calculating the specific amount of solar radiation reaching the ground (Rs) based on light spectrums and the sun's position. By categorizing these SBAI results into zones-from extremely dry to humid-we created a clear map of environmental stress. Finally, by linking these heat patterns to land-use types, the research reveals how different terrains shape local climates and vulnerability to drought. Ultimately, the study proves that merging different MODIS datasets offers a powerful, adaptable way to monitor ecological decline and climate-driven drying, providing vital information for smarter land management and climate resilience.

Keywords: Land Surface Temperature (LST, Surface-Brightness-based Aridity Index (SBAI), MODIS Multi-Sensor Fusion, Spatiotemporal Thermal Dynamics, Google Earth Engine (GEE), Land Use and Land Cover (LULC), Aridity Classification, Climate Change Monitoring

Introduction

As the global water cycle speeds up and deserts expand, we face a major threat to both our environment and our food supplies. To understand these shifts, we look at Land Surface Temperature (LST), which acts like a thermometer for the planet's energy levels and is closely linked to how dry a region becomes. Because traditional weather stations are often too far apart to show the full picture, we now rely on advanced satellite networks. These "eyes in the sky" allow us to track temperature changes day and night with incredible detail, giving us a solid way to measure the stress on fragile ecosystems. A key part of this research involves looking at how heat interacts with how much sunlight the ground reflects. Thanks to modern technology, we can use tools like the Surface-Brightness-based Aridity Index (SBAI). This index calculates the gap between daytime and nighttime temperatures while factoring in surface brightness and solar energy. To get this right, researchers carefully filter out clouds and interference from satellite data (like MODIS) to ensure the readings are clean. This high-tech approach helps us categorize land on a scale from bone-dry "hyper-arid" zones to lush, humid environments based on how the ground holds onto heat.

Finally, we have to consider how human activity changes the landscape. When we swap forests or grasslands for concrete cities or industrial farms, we mess with the way the Earth "breathes" heat. This often leads to hotter urban areas and drier local climates. By comparing maps of land use with our aridity data, we can clearly see how our building and farming habits are driving temperature swings and drought. Understanding these links is vital if we want to create smart climate strategies and protect our natural resources in a world that is getting warmer by the day.

Study Area

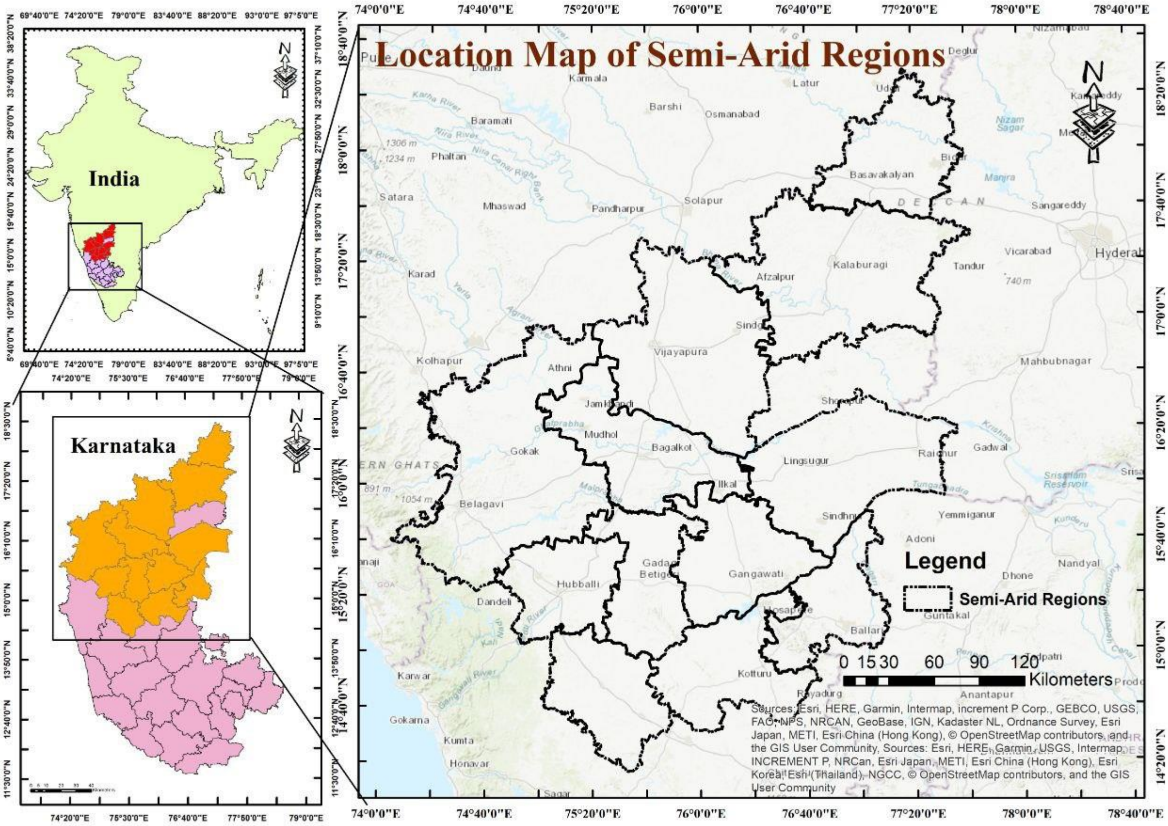


Fig 1 : Semi-arid Region of Karnataka

This research centers on the semi-arid heartlands of Karnataka, India, specifically focusing on the North Interior and Central Dry Zones of the Deccan Plateau. Spanning between latitudes 11°30' N to 18°30' N and longitudes 74° E to 78°30' E, this semi-arid expanse accounts for roughly 74% or about 142,464 square kilometres of the state's total territory. The landscape is defined by its rolling, undulating terrain, typically sitting at elevations between 450 and 900 meters. Because these areas sit on the leeward side of the Western Ghats, they are shielded from heavy rains by a significant rain-shadow effect. This geographic positioning makes inland districts like Vijayapura, Raichur, Kalaburagi, and Chitradurga some of the most arid and drought-sensitive regions in India. The climate here is classically tropical semi-arid, characterized by intense heat and highly unpredictable rainfall. Most of the area receives a meager 450 mm to 750 mm of rain annually, with the vast majority arriving during the southwest monsoon from June to September. Temperatures can be punishing; summer highs often soar to between 43°C and 45°C, especially in northern plains like Raichur, while winter temperatures fluctuate between 9°C and 27°C. The combination of searing heat and low humidity causes water to evaporate much faster than it is replenished by rain, creating a persistent moisture deficit and "ustic" soil conditions where the ground remains dry for long stretches of the year.

The local ecology and soil types further shape how the region handles this thermal stress. In the north, the land is dominated by deep black soils known as Vertisols, while red sandy loams, or Alfisols, are more common in the central and southern dry belts. Farming in these zones is almost entirely dependent on rainfall, with staple crops like Jowar, Ragi, and various pulses remaining highly vulnerable to the shifting patterns of aridity. Given the rapid changes in land use and the alarming decline in groundwater levels, using MODIS satellite data to track Land Surface Temperature (LST) is essential for understanding how these environmental shifts are intensifying heat and dryness across the landscape.

Methodology and Data Processing

To investigate local climate patterns, this study primarily relies on multi-temporal satellite data from the MODIS sensors on the Terra and Aqua satellites. We specifically utilized the MOD11A1 product, which provides Land Surface Temperature (ΔLST) and Emissivity at a 1 km resolution, to track daily thermal changes. To maintain high data standards, we applied a strict quality control (QC) protocol. By using bitmasking on the "QC_Day" and "QC Night" layers, we filtered out unreliable data caused by cloud cover, heavy aerosols, or sensor glitches. These raw temperature values were then converted into Kelvin using a 0.02 scaling factor. We calculated the average annual daytime and night time temperatures to find the thermal variance (ΔLST), representing the gap between day and night surface heat. Alongside the thermal data, we incorporated surface reflectance from the MODIS MCD19A1 (MAIAC) product to better understand how the ground interacts with solar energy. Our workflow for assessing aridity involved a custom cloud-masking routine that used bitwise operations on the "Status_QA" band to strip away cloud shadows and peripheral interference. We then created a median composite of this filtered data to establish a stable baseline for the study period. A central element of our approach is the Solar-Brightness-based Aridity Index (SBAI), which gauges aridity by comparing temperature swings to the surface radiation budget. We estimated net shortwave radiation (RS) through an empirical formula using spectral bands 1, 2, and 3, while adjusting for the solar zenith angle to ensure consistent light geometry across the dataset.

The final aridity profile was determined by the ratio of temperature variance to solar radiation (SBAI =ΔLST/RS). Using a threshold-based model, we sorted these results into five categories: areas with an SBAI of 0.015 or lower were labeled as the most humid (Class 5), while those above 0.025 were identified as hyper-arid (Class 1). Finally, we overlaid these aridity trends with Land Use and Land Cover (LULC) maps. This allowed us to examine how different environments-ranging from urban centers and water bodies to dense vegetation-shape local heat patterns. This integrated method provides a detailed look at how specific land characteristics drive changes in aridity and thermal stability over time and space.

Results and Detailed Analysis

Spatiotemporal Variations in Land Surface Temperature (LST)

Temperature Data

Name	2000	2005	2010	2015	2020
Bidar	25.87	25.49	26.36	26.98	25.97
Kalaburagi	26.23	25.84	26.77	27.18	26.38
Vijayapura	26.14	25.91	26.90	27.08	26.37
Raichur	26.92	26.40	27.58	27.64	27.19

Bagalakote	25.74	25.50	26.29	26.39	25.81
Belagavi	23.95	23.98	24.40	24.55	24.27
Dharwad	24.54	24.51	24.84	25.04	24.63
Gadag	25.33	25.10	25.64	25.77	25.29
Koppal	25.87	25.50	26.24	26.27	25.90
Ballari	26.23	25.89	26.37	26.50	26.40
Vijayanagara	25.87	25.50	26.24	26.27	25.90
Haveri	25.18	25.07	25.39	25.53	25.23

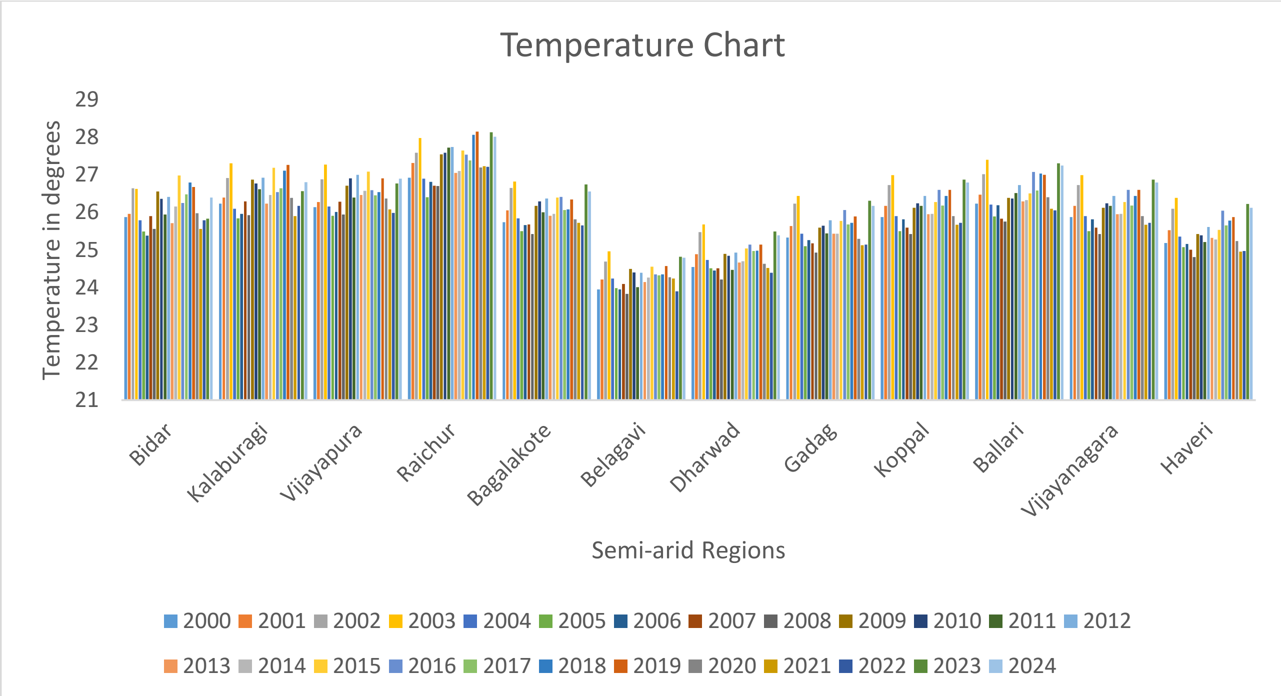
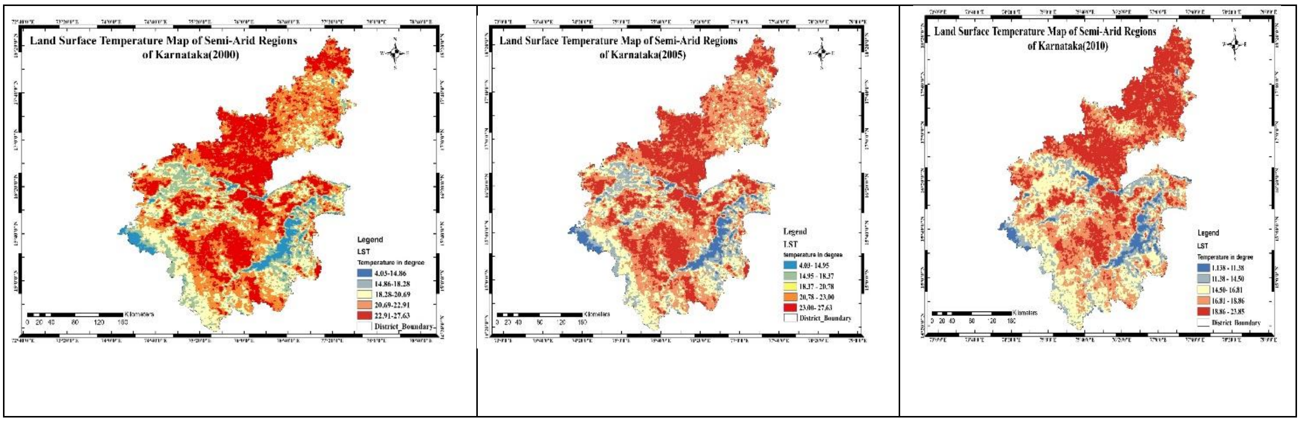


Chart 1 : Temperature Chart of Semi-arid region of Karnataka



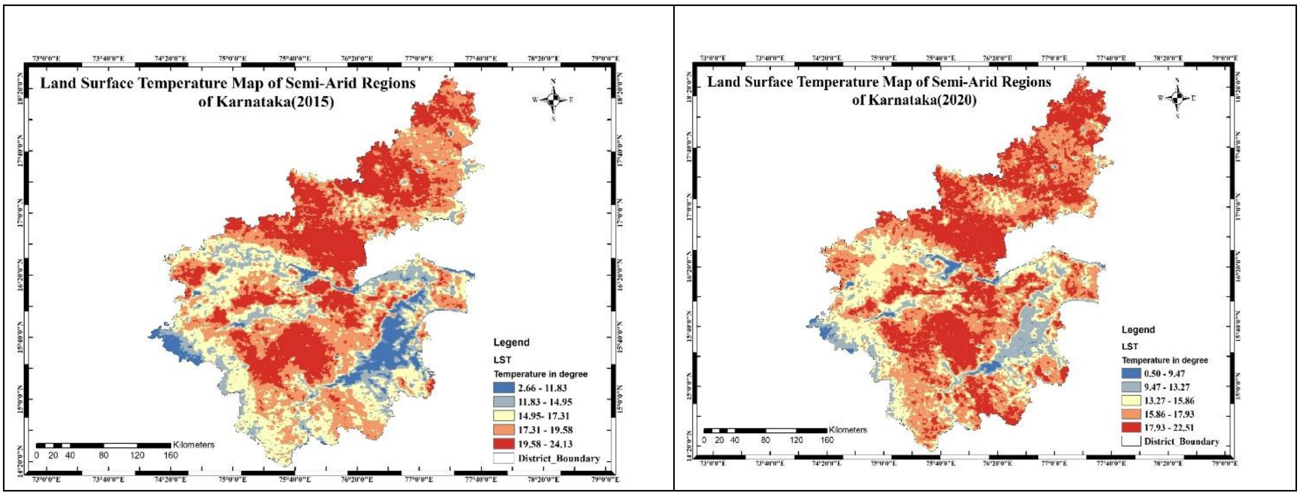


Fig 2 : Land surface temperature map of semi-arid region of karnataka

To understand the region's thermal behavior, we analyzed 2024 satellite data from the MODIS (MOD11A1) sensor, which highlighted a clear divide between daytime and nighttime surface temperatures. We used a strict bitmasking process to clean the data, ensuring that issues like cloud interference or atmospheric haze didn't distort the results. The findings show a wide temperature spectrum, spanning from a chilly -20°C to a scorching 50°C. By subtracting the nighttime temperatures from the daytime peaks, we created a "difference map" that acts as a window into the land's thermal inertia. Essentially, areas that experience extreme temperature swings during the day usually lack moisture and vegetation, while more consistent thermal patterns point to landscapes with better water retention or thick forest canopies that provide natural cooling.

Surface-Brightness-based Aridity Index (SBAI) and Radiative Flux

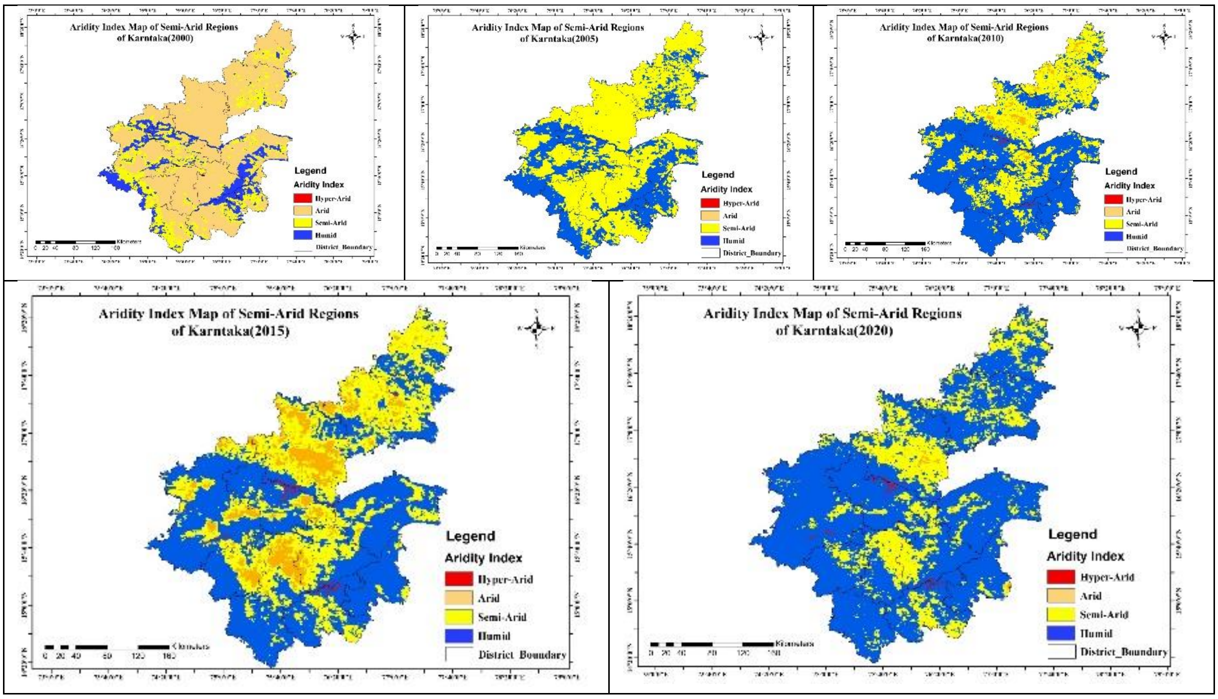


Fig 3 : Aridity index map of semi-arid region of karnataka

To measure variations in aridity, we developed the Solar-Brightness-based Aridity Index (SBAI) by combining surface temperature shifts with reflectance data from the MCD19A1 dataset. At the heart of this calculation is a specific radiative flux formula:

$$F = (1 - (0.160\ r_1 + 0.291\ r_2 + 0.243\ r_3))\ 1363 \cos(0.0001)$$

In Simplified Form;

$$F = 1363 - 218.08\ r_1 - 396.633\ r_2 - 331.209\ r_3$$

This equation accounts for shortwave albedo across three key spectral bands to estimate the energy reaching the surface. By calculating the ratio between the day-night temperature gap and this radiative value, the SBAI pinpointed areas suffering from severe moisture loss. The final analysis produced an aridity map divided into five environmental categories. Regions with index values exceeding 0.025 were identified as hyper-arid, defined by intense light reflection and wide temperature swings. Conversely, values of 0.015 or lower pointed to humid areas or stable water bodies where thermal fluctuations are minimal.

Integration of LULC Dynamics and Thermal Response

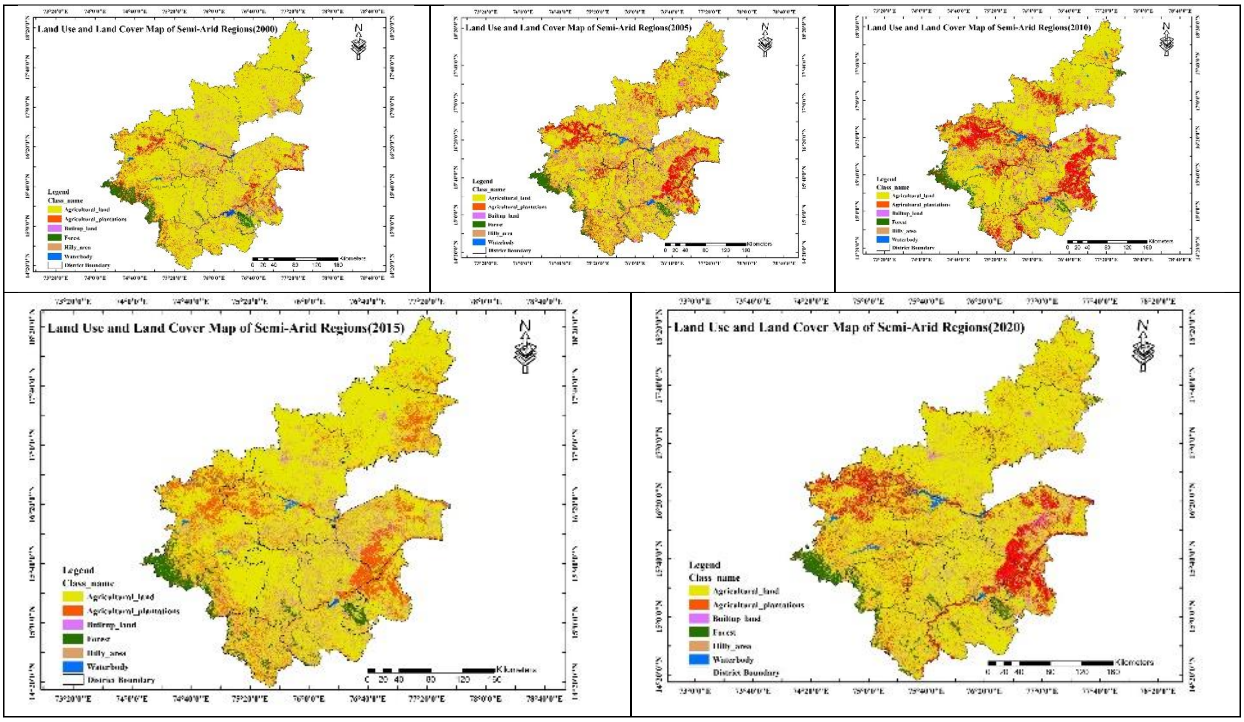


Fig 4 : Land Use and Land Cover map of semi-arid region of karnataka

Our analysis reveals that the way land is used and covered (LULC) plays a major role in how aridity and thermal stress are spread across the landscape. According to our findings, different types of terrain-such as city centers, farms, and forests-each leave a distinct mark on the SBAI classification. For instance, urban environments often show much higher day-to-night temperature gaps because they lack the cooling effect of plants and moisture, which pushes them into more extreme aridity categories. In contrast, agricultural zones experience a shifting thermal profile; during the height of the growing season, active plant life cools the surface through evaporation, leading to a lower SBAI. However, once crops are harvested and the ground is left bare, these areas quickly shift toward a semi-arid state. Ultimately, this connection shows that while regional weather sets the overall stage, it is the specific local land characteristics that truly dictate the most intense heat and aridity patterns.

Accuracy Assessment and Data Quality

The credibility of our findings is backed by a thorough, multi-step quality assurance (QA) protocol used while processing the MODIS data. We applied precise bitmasking to both the temperature and reflectance datasets to strip away low-quality pixels affected by cloud shadows, heavy aerosols, or sensor glitches. Furthermore, by using a median reduction method on the data collections from 2020 and 2024, we ensured that the resulting SBAI and LST layers reflect consistent, long-term annual trends instead of temporary weather spikes. This rigorous approach provides a reliable foundation for monitoring climate shifts and informing land management policies with high confidence.

Discussion and Conclusion

Discussion

By merging data from multiple MODIS satellite sensors, specifically the MOD11A1 and MCD19A1 products, we can see how surface heat and regional dryness are closely linked. We used the difference between daytime and nighttime surface temperatures as a main indicator of how the ground swaps energy with the atmosphere. When these temperature swings are wide, it usually signals higher aridity, a trend clearly captured by our Solar-Brightness-based Aridity Index (SBAI). This approach highlights how much the local climate depends on surface reflectivity and the angle of the sun. Additionally, our look at Land Use and Land Cover (LULC) shows that losing greenery or expanding urban areas makes heat stress worse, which in turn speeds up the drying of the landscape.

These results support global initiatives like the UN's Sustainable Development Goals-specifically Goal 13 for Climate Action and Goal 15 for Life on Land-by offering precise tools to track drought and desertification. On an international scale, this work matches the United Nations Convention to Combat Desertification (UNCCD) and its push for Land Degradation Neutrality. Closer to home, it aligns with India's National Action Plan on Climate Change (NAPCC) and the PMKSY irrigation scheme, both of which call for smarter water use in dry zones. For a state like Karnataka, which often faces harsh droughts and unpredictable rains, this data is vital for the State Action Plan on Climate Change. By pinpointing "hyper-arid" hotspots using the SBAI, local leaders can roll out specific fixes, like drought-resistant crops or better irrigation, to protect the economy from extreme heat shifts.

Conclusion

Our research highlights how effectively multi-sensor satellite data can track changes in local heat and aridity over time. We found that the SBAI is a dependable tool for sorting environments-from bone-dry deserts to lush, humid zones-because it successfully bridges the gap between ground temperature swings and solar energy absorption. By connecting these thermal patterns to changes in land use, it becomes clear that human-driven land development is a major force behind shifting local climates.

This methodology offers a flexible model for environmental monitoring that can be applied at any scale, from local regions to entire nations, helping to meet global climate goals. By linking these satellite-derived insights to Sustainable Development Goals (SDGs), especially those focused on resilient farming and nature conservation, this work sheds light on the complex relationship between the earth and the atmosphere. For a region like Karnataka, which frequently faces water scarcity, these data-backed strategies are vital for building a climate-ready future. They ensure that decisions regarding farming and water management are based on accurate, real-world observations. Looking ahead, combining these environmental indices with long-term economic and social data will be key to refining how we adapt to a warming planet.

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