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From Past to Future: Uzbekistan’s Climate Signals Through Time

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Abstract

This study investigates long-term trends and future projections of key climate variables, evapotranspiration, land surface temperature (LST), normalized difference vegetation index (NDVI), soil moisture and precipitation, across Uzbekistan using multi-source satellite and reanalysis datasets within the Google Earth Engine (GEE) platform. Spanning the period from 1995 to 2024, the analysis applied the Mann-Kendall test to assess the statistical significance of observed trends, revealing significant increases in LST, NDVI and evapotranspiration, while trends in soil moisture and precipitation were statistically insignificant. To forecast future trajectories (2025-2050), the autoregressive integrated moving average (ARIMA) model was employed, indicating continued warming, vegetation growth and rising evapotranspiration, with marginal changes in precipitation and a possible decline in soil moisture. Model performance was evaluated through a 70/30 training-test split, where NDVI achieved the highest R^2 (0.64), followed by precipitation, LST, evapotranspiration and soil moisture. These results suggest ARIMA can capture temporal patterns to a degree, but more extensive datasets and integrated models may be necessary for higher accuracy. To sum up, findings point to a warming and drying climate scenario, underscoring the urgency of proactive land and water management strategies to ensure ecological and agricultural sustainability in Uzbekistan under evolving climatic conditions.

1. Introduction

In the context of accelerating climate change and increasing environmental variability, the continuous monitoring of key climate parameters has become essential for understanding ecosystem dynamics and supporting sustainable resource management. Remote sensing technologies offer a powerful means of capturing large-scale environmental data with high spatial and temporal resolution, overcoming the limitations of traditional in-situ measurements. Parameters such as vegetation condition (e.g., normalized difference vegetation ratio - NDVI) (Fayech and Tarhouni, 2021), land surface temperature (LST) (Ozelkan et al., 2014), evapotranspiration (Vinukollu et al., 2011) and precipitation (Levizzani and Cattani, 2019) can be effectively monitored using satellite-based observations, enabling comprehensive assessments of climatic and ecological trends over extended time periods. The capacity of remote sensing to provide consistent, repeatable and objective measurements across diverse geographic regions makes it an indispensable tool in climate analysis, hydrological modelling, drought and flood risk assessment and agricultural and water resource planning. As such, remote sensing has emerged as a cornerstone of modern environmental monitoring systems (Ahmadi et al., 2023; Odongo, 2023), contributing significantly to both scientific research and evidence-based policy-making.

A wide variety of satellite-based remote sensing datasets have become indispensable for monitoring terrestrial and atmospheric components of the climate system. Among the most extensively utilized platforms, the Landsat mission series, jointly operated by National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS), has provided continuous medium-to-low-resolution imagery since the 1970s, enabling the analysis of LST (Berroir et al., 1998), vegetation indices (Running and Nemani, 1988) and land cover change (Reid et al., 2000). Complementing Landsat, the Sentinel missions under the Copernicus Programme of the European Space Agency (ESA) offer higher temporal resolution and multispectral capabilities, particularly Sentinel-2 for vegetation monitoring (Addabbo et al., 2016) and Sentinel-1 for soil moisture estimation through synthetic aperture radar (SAR) data (Chatterjee et al., 2020). MODIS (Moderate Resolution Imaging Spectroradiometer) on board the Terra and Aqua satellites remains a key source for daily estimates of evapotranspiration (Mu et al., 2013), vegetation dynamics (Beck et al., 2006) and surface temperature (Phan and Kappas, 2018) at global scale. For precipitation, products like CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) integrate satellite observations with meteorological station data to produce spatially detailed precipitation estimates (Funk et al., 2015; Paredes-Trejo et al., 2017), particularly valuable in data-scarce regions. Soil moisture and land surface fluxes are often derived from reanalysis datasets such as ERA5-Land, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), which assimilates both remote sensing and ground-based measurements into physically consistent, gridded outputs. These diverse remote sensing platforms collectively provide a comprehensive toolkit for evaluating the spatial and temporal dynamics of key environmental variables, supporting robust time series analyses and climate forecasting efforts worldwide.

In recent years, the advent of cloud-based geospatial processing platforms such as Google Earth Engine (GEE) has significantly transformed the way large-scale environmental data analyses are conducted. GEE provides researchers with direct access to a vast catalogue of pre-processed satellite imagery and climate datasets, such as MODIS, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Landsat, Sentinel, CHIRPS and ERA5, eliminating the need for local data storage and extensive pre-processing workflows. Its powerful parallel computing infrastructure enables rapid processing of petabyte-scale datasets, which is particularly advantageous for long-term time series analyses across large geographic regions. Furthermore, GEE’s JavaScript- and Python-based APIs facilitate flexible and reproducible workflows, allowing users to apply complex spatial and temporal operations, visualize results in real time and share code openly for collaborative research. These capabilities make GEE an especially valuable tool for climate and environmental studies, where multi-source data integration, high temporal granularity and large spatial coverage are essential for deriving meaningful insights and forecasts.

Its capabilities have made GEE an indispensable platform for environmental and climate research in recent years, and many studies have leveraged its computational efficiency and extensive data catalogue to conduct large-scale spatiotemporal analyses. Ravanelli et al., (2018) demonstrated the potential of GEE and the Climate Engine tool to process extensive Landsat archives for long-term monitoring of surface urban heat island (SUHI) dynamics and their link to land cover change, highlighting consistent SUHI intensification across six U.S. metropolitan areas from 1992 to 2011. Hao et al., (2019) employed multi-source remote sensing data within GEE to assess land use/cover change and climate variability in the Three Gorges Reservoir Catchment (China) from 2000 to 2015, revealing that land transformation, particularly urban expansion and reforestation, influenced regional vegetation dynamics and surface temperature patterns. Using 570 Landsat images and meteorological data from 1984 to 2019 via GEE, Abujayyab et al., (2021) revealed a significant shrinkage of Burdur Lake (Türkiye)'s surface area, linked to seasonal variations in temperature, precipitation, radiation and evapotranspiration, with implications for sustainable water management in Türkiye. Utilizing GEE and 40 years of Palmer drought severity index (PDSI) data, Venkatappa et al., (2021) quantified the spatial and temporal impacts of droughts and floods on cropland and crop production in Southeast Asia, revealing severe damage to rainfed agriculture and identifying regional vulnerabilities requiring targeted policy interventions. Rahaman and Shermin (2022) used GEE to analyse six years of Sentinel-1 and Landsat-8 data in northeast Bangladesh, revealing a consistent negative correlation between flood extent and vegetation health, alongside increasing LST in flood-affected areas. Moazzam et al., (2022) used Landsat and climate datasets on GEE and revealed a surprising increase in snow cover area in the Astore and Shigar basins of the Upper Indus Basin from 1991 to 2021, likely driven by rising precipitation and localized cooling trends at higher elevations. Using GEE and multi-source satellite data, Shetty et al., (2022) revealed that rapid urbanization in Dakshina Kannada district between 2001 and 2019 significantly altered land cover, increased surface temperatures and reduced evapotranspiration, particularly in forest and built-up areas, highlighting the climatic consequences of LULC change. Using MODIS data and GEE, de Almeida et al., (2023) assessed temperature trends in Montesinho Natural Park (Portugal) from 2003 to 2021, revealing stable summer temperatures but rising winter night-time LST, with strong correlations between vegetation indices and diurnal temperature patterns. Gadekar et al., (2023) used GEE, remote sensing data and machine learning to analyse LST, NDVI and normalized difference built-up index (NDBI) in Nashik, revealing intensified UHI effects and strong LST correlations with vegetation loss and urban expansion between 2015 and 2019. Sanchez et al., (2023) presented a GEE-based framework utilizing open data to assess environmental vulnerabilities in Kosovo, emphasizing the critical role of data accessibility and institutional capacity in addressing climate change and sustainability challenges in developing nations. By integrating JRC Global Surface Water layers with MODIS-based climatic variables on GEE, Kazemi Garajeh et al., (2024) used JRC surface water datasets and MODIS-derived climatic indicators within GEE to reveal that rising air temperature and evapotranspiration are key drivers of surface water loss in the Lake Urmia Basin between 2000 and 2021, with minimal influence from precipitation. Erdoğan and Yılmaz (2024) demonstrated clear evidence of climate-driven shifts in Türkiye's environmental parameters, with evapotranspiration and vegetation indices showing strong interdependence and pronounced spatial variability in response to changing precipitation and temperature patterns. GEE-based analysis of LULC, LST and normalized difference water index (NDWI) from 2000-2023 showed that Lake Victoria's surface area gradually expanded, urban and cropland areas increased, and LST remained relatively stable, though extreme water level rise displaced over 29,000 people in 2020 (Ali et al., 2024). Using multi-sensor satellite data processed through GEE, Halder and Pereira (2024) quantified mangrove degradation and cyclone impacts in the Sundarbans Biosphere Reserve between 2017 and 2022, highlighting the role of remote sensing in assessing coastal vulnerability to sea-level rise and extreme weather events. Radwan et al., (2025) used GEE and 20 years of CHIRPS and MODIS data; and found declining rainfall-vegetation correlation, rising land surface temperatures and increasing climatic variability in southern India, highlighting growing vulnerability to droughts, floods and agricultural stress. Using time-series remote sensing data from 1995-2023, Serifoglu Yilmaz (2025) analysed the climatic impacts of five dam reservoirs in Artvin, Türkiye, revealing post-construction increases in temperature, evapotranspiration, and heat index, alongside vegetation growth, but no significant change in precipitation.

The motivation behind this study stems from the growing need to better understand the long-term spatiotemporal dynamics of key hydro-climatic variables in the context of climate variability and water resource challenges in Central Asia. Uzbekistan, characterized by its arid to semi-arid climate and high dependence on transboundary water resources, faces increasing pressure from rising temperatures, shifting precipitation patterns, and land degradation. These environmental stressors have profound implications for agriculture, ecosystem stability, and sustainable development in the region. Despite the critical importance of monitoring indicators such as evapotranspiration, land surface temperature, vegetation health, soil moisture and precipitation, comprehensive and integrated assessments based on long-term remote sensing data remain limited. This study aims to address this gap by utilizing multi-source satellite and reanalysis datasets to evaluate historical trends and forecast future trajectories of these variables through time series modelling. By doing so, the research seeks to contribute valuable insights for climate impact assessment, water resource planning, and regional adaptation strategies.

Section 2 will outline the geographic context of Uzbekistan and describe the remote sensing datasets employed in the analysis, along with a detailed explanation of the forecasting methodology applied to the climate variables and some details for the Mann-Kendall test used to assess the significance of the trends. Section 3 is dedicated to presenting and interpreting the results of the forecasts. Finally, Section 4 will present a summary of the concluding remarks.

2. Material and Methods

2.1 Study Area

Uzbekistan is a double landlocked country located in Central Asia, situated between the Amu Darya and Syr Darya rivers. The country shares borders with Kazakhstan to the north, Turkmenistan to the west, Kyrgyzstan and Tajikistan to the east and southeast and Afghanistan to the south. With a population of approximately 37 million, Uzbekistan covers a total area of 447,400 km^2, of which about 43,000 km^2 is used for agricultural purposes (Khasanov et al., 2022; World Bank, 2024; Makhmudova et al., 2023).

Around 80% of Uzbekistan's land consists of plains and desert areas. In addition to vast lowland plains and deserts, the landscape is also characterized by foothills and mountain ranges. The country's highest point is located in the Hisar Mountains, reaching an elevation of 4,643 meters, while the lowest point is the Sarygamysh Depression, approximately 20 meters below sea level (Belolipov et al., 2012).

The climate across Uzbekistan is arid and continental, with significant seasonal and regional variability in temperature and precipitation. In the arid lowlands of the northwest, annual precipitation generally remains around 70-100 mm, whereas in the mountainous regions it can occasionally exceed 1,200 mm. Most precipitation occurs between late autumn and early spring, with peak rainfall typically observed in March and April (Khasanov et al., 2022; Makhmudova et al., 2023).

The prolonged summer months are extremely hot and dry, with temperatures often exceeding 45°C in some areas. Winters, on the other hand, vary by region: while the southern parts experience milder winters, the northern regions are affected by severe cold and temperatures can occasionally drop below -37°C (Belolipov et al., 2012).

2.2 Data Used

In this study, to evaluate evapotranspiration, the global 8-day actual evapotranspiration product derived from NASA's MODIS sensor was utilized (Mu et al., 2013). The dataset, available in the GEE library under the ID "MODIS/061/MOD16A2," estimates the total evapotranspiration from the land surface to the atmosphere, including both evaporation and plant transpiration. This product has a spatial resolution of 500 meters and covers the period from 2021 to the present. The evapotranspiration values are provided in units of kg/m^2, which are practically equivalent to millimetres (mm) for hydrological analyses (Google Earth Engine, 2025). Since this dataset does not include data prior to 2021, the earlier version, identified as "MODIS/006/MOD16A2," was used to analyse the period between 2001 and 2022.

The Landsat satellite program provided researchers with long-term and continuous temporal data (Wulder et al., 2019). Thermal Infrared (TIR) imagery, which serves as the primary data source for LST calculations, is fully accessible on the GEE platform, starting from Landsat 4, launched in 1982, up to the most recent Landsat 9 data. In this study, Landsat 5 imagery (GEE ID: "LANDSAT/LT05/C02/T1_L2") was used for the 1995-2012 period, while Landsat 8 imagery (GEE ID: "LANDSAT/LT08/C02/T1_L2") was used for the post-2012 period. For LST analysis, the thermal bands 'ST_B6' and 'ST_B10' were utilized from Landsat 5 and Landsat 8, respectively.

Vegetation indices are essential tools used to assess the distribution and health of vegetation in ecosystems. Among them, the NDVI is widely used in environmental studies, as it provides insights into vegetation conditions based on the reflectance properties of chlorophyll in plants (Zhu et al., 2008). In this study, NDVI calculations were based on surface reflectance imagery derived from Landsat 5 TM and Landsat 8 satellite data.

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{1}$$

where, NIR represents the near-infrared band, while RED refers to the red band. NDVI values range from -1 to +1 and reliably indicate land surface characteristics. High NDVI values correspond to dense and healthy vegetation, while low values indicate sparsely vegetated or non-vegetated surfaces such as soil, water, ice or snow. This range allows researchers to monitor land use and vegetation changes over time (Fu et al., 2023; Serifoglu Yilmaz, 2025). In this study, the temporal variation of NDVI values was examined for the period between 1995 and 2024.

For the soil moisture analyses, the ERA5-Land reanalysis dataset, developed by the ECMWF under the Copernicus Climate Change Service (C3S) of the European Commission, was utilized (Hersbach et al., 2020; Muñoz-Sabater et al., 2021). ECMWF is an independent research institution that produces global numerical weather predictions and climate data, serving 35 partner countries and a wide user community. Available on the GEE platform under the identifier "ECMWF/ERA5_LAND/HOURLY", ERA5-Land represents the land component of the ERA5 series and provides enhanced data quality compared to previous versions (Muñoz-Sabater et al., 2021). In this study, the 'volumetric_soil_water_layer_1' band was used to assess soil moisture. This band represents the topsoil layer (approximately 0-7 cm deep) and provides hourly data on volumetric soil water content. Expressed in units of m^3/m^3, it quantifies the amount of water present per unit volume of soil, allowing for a quantitative assessment of soil moisture status. The soil moisture analysis was conducted for the time period spanning from 1995 to 2024.

The CHIRPS dataset was used to analyse precipitation. Developed by NASA in collaboration with the Climate Hazards Group at the University of California, Berkeley, this dataset combines satellite observations with ground station data to provide high spatial accuracy (Meshesha et al., 2024). Available on the GEE platform under the identifier "USCB-CHG/CHIRPS/DAILY", the dataset offers daily temporal resolution and was used in this study at a spatial resolution of 5.56 km. Precipitation distributions were analysed for the period between 1995 and 2024.

2.3 Future Projection with ARIMA

The future estimations for the climate parameters focused were done with the ARIMA, which is a widely used statistical modelling technique for analysing and forecasting time series data. It combines three components (Dimri et al., 2020): autoregression (AR), which uses the relationship between a current value and its past values; integration (I), which involves differencing the data to make it stationary (i.e., removing trends and seasonality); and moving average (MA), which models the error of the prediction as a linear combination of past forecast errors. By identifying and estimating the appropriate parameters for these components, ARIMA can produce accurate forecasts and uncover underlying trends in historical data, making it useful in various fields such as economics (Aljandali and Tatahi, 2018), climate studies (Dimri et al., 2020) and environmental monitoring (Kumar and Jain, 2010).

2.4 Trend Analysis

The Mann-Kendall test is a non-parametric statistical method widely used to detect trends in time series data without requiring the data to be normally distributed (Mann, 1945; Kendall, 1975). It evaluates whether there is a monotonic upward or downward trend over time, based on the ranks of the observations rather than their raw values. This makes it particularly suitable for analysing environmental and climate data, which often exhibit non-linear patterns and contain outliers. In this study, the Mann-Kendall test was applied to assess the statistical significance of trends

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observed in key climate indicators LST, evapotranspiration, NDVI, precipitation and soil moisture. A significant result indicates the presence of a consistent trend over the study period, while a non-significant result suggests that no clear directional change was detected.

3. Results and Discussion

Figure 2 illustrates both the actual annual total evapotranspiration values from 2001 to 2024 and the values projected for the period 2025-2050 using the autoregressive integrated moving average (ARIMA) model. Between 2001 and 2022, annual ET values remained relatively stable, fluctuating between approximately 70 mm/year and 130 mm/year. However, a noticeable increase was observed in 2023 and 2024, with annual ET values rising to 184 mm/year and 218 mm/year, respectively. These recent spikes caused a distinct upward trend in the overall time series. Based on this pattern, the ARIMA model forecasted ET values between 180 mm/year and 265 mm/year for the period extending to 2050.

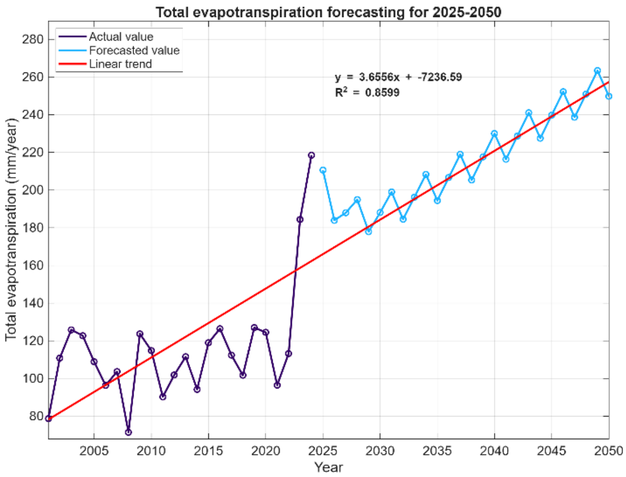

Figure 2. Actual and forecasted annual total evapotranspiration values.

This suggests that the region may be entering a phase of heightened evapotranspiration, which could be driven by several interrelated factors. Rising temperatures due to climate change may be increasing atmospheric demand for moisture, while potential changes in land cover, such as agricultural intensification, expansion of irrigated croplands or afforestation efforts, could also enhance evapotranspiration rates. Additionally, prolonged growing seasons and shifts in vegetation phenology could be contributing to higher annual water fluxes.

The upward trend in evapotranspiration may have critical implications for water availability, agricultural planning and ecosystem services in Uzbekistan. For instance, increased evapotranspiration could lead to reduced soil moisture and higher irrigation demands, placing additional stress on already limited water resources in the region. Moreover, if the trend reflects a broader climatic shift, it may necessitate the revision of current hydrological models and resource management strategies to ensure long-term sustainability.

Figure 3 presents the observed annual mean LST values for the period 1995-2024, along with the values projected for 2025-2050 using the ARIMA model. As shown in the figure, the observed LST values exhibit considerable interannual variability. Notably, abnormal spikes in LST were recorded in the years 2006, 2007 and 2008. Despite this variability, the linear trend of LST over the observed period is clearly upward.

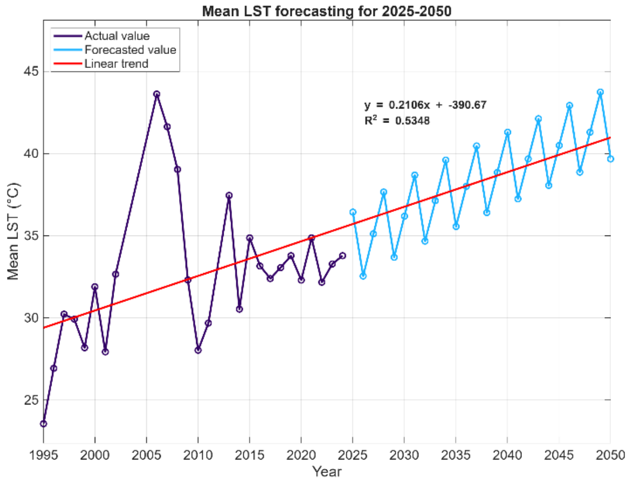

Figure 3. Actual and forecasted annual mean LST values.

The ARIMA-based projections indicate that annual mean LST may reach as high as 43°C by 2050. This indicates a substantial warming trend, which could have significant consequences for regional climate dynamics, water availability and land productivity. An increase in surface temperatures of this magnitude could intensify evapotranspiration rates, exacerbate drought conditions and place further pressure on agricultural systems and natural ecosystems. Furthermore, rising LST may contribute to heat stress, reduce crop yields and increase the frequency of extreme weather events.

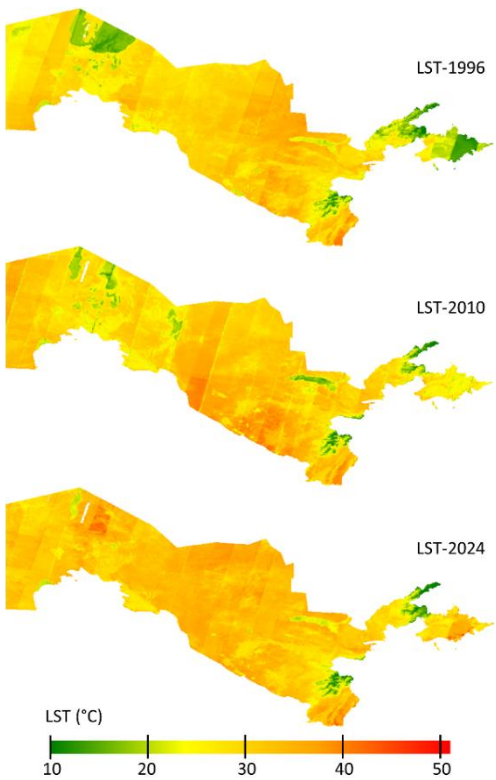

Figure 4. Mean LST maps produced for 1996, 2010 and 2024.

If these projections hold true, it underscores the need for proactive adaptation strategies, such as developing heat-tolerant crop varieties, improving irrigation efficiency and implementing climate-resilient land-use planning. Continuous monitoring and integration of satellite-based indicators like LST will be critical for guiding policy decisions and ensuring sustainable development under changing climatic conditions.

Figure 4 illustrates the spatial distribution of mean LST for the years 1996, 2010 and 2024. A clear warming trend is evident in the figure, with a noticeable increase in LST values over time, confirming the progression of surface temperature rise across Uzbekistan.

Figure 5 displays the annual mean NDVI values observed between 1995 and 2024, along with ARIMA-based projections of annual mean NDVI extending to 2050. Uzbekistan is characterized by a highly arid climate and a relatively sparse vegetative cover in proportion to its land area. Accordingly, the observed annual NDVI values during the 1995-2024 period remained relatively low, fluctuating between approximately 0.04 and 0.085. As indicated by the linear trend line in Figure 4, NDVI has shown a modest upward trajectory over time.

The ARIMA forecast suggests that the annual average NDVI could reach up to 0.1 by 2050. While this represents a slight improvement, such a level of vegetative density remains critically low for a country grappling with persistent drought conditions.

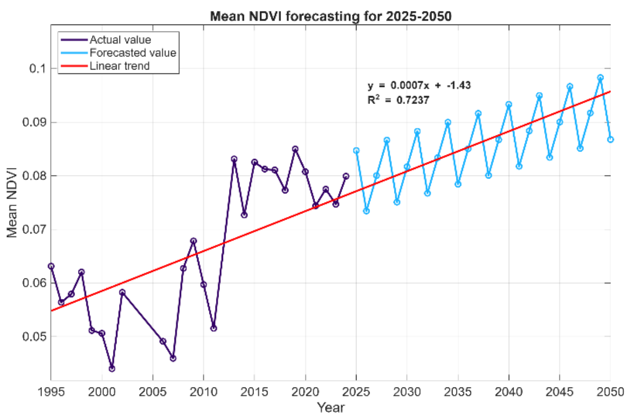

Figure 5. Actual and forecasted annual mean NDVI values.

In this context, the projections emphasize the ongoing vulnerability of Uzbekistan's ecosystems and agricultural productivity. An NDVI value around 0.1 indicates limited vegetative biomass, insufficient to sustain robust ecological functions or extensive agricultural activities without substantial external support such as irrigation. This scenario highlights the urgent need for sustainable land management practices, afforestation efforts and investment in resilient agricultural systems to enhance vegetation cover and mitigate the adverse effects of land degradation and climate variability. Integrating satellite-based vegetation indices like NDVI into long-term environmental planning can help guide effective adaptation strategies in arid and semi-arid regions like Uzbekistan.

Figure 6 displays the spatial distribution of mean NDVI for the years 1996, 2010 and 2024. The maps reveal a gradual improvement in vegetation cover over time, with the most notable increases observed in the eastern regions of Uzbekistan.

Figure 7 illustrates the annual mean soil moisture values observed between 1995 and 2024, as well as the projected values up to 2050 based on the ARIMA model. As seen in the figure, the annual average soil moisture during the historical period varied between approximately 0.11 m^3/m^3 and 0.18 m^3/m^3. A downward trend in soil moisture is evident as the data approaches 2024. The ARIMA-based projections suggest that mean soil moisture levels may decline further, potentially reaching as low as 0.12 m^3/m^3 by 2050.

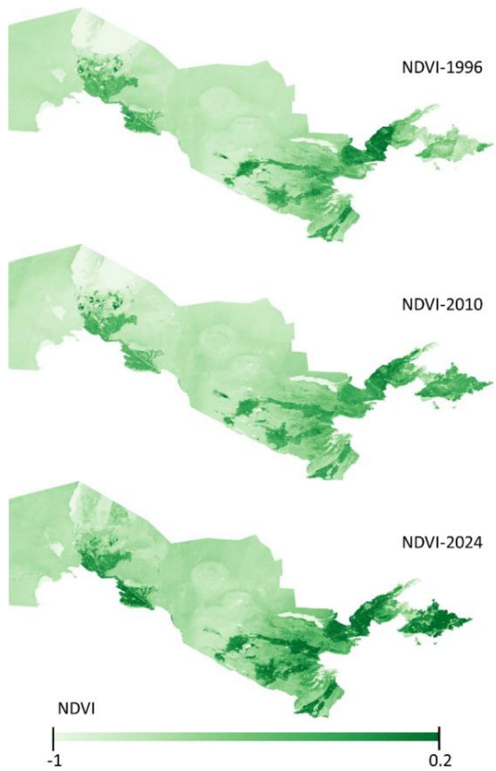

Figure 6. Mean NDVI maps produced for 1996, 2010 and 2024.

This situation underscores a concerning trajectory in Uzbekistan’s environmental conditions. Declining soil moisture levels may directly affect plant water availability, reduce agricultural yields and contribute to land degradation and desertification, especially in already arid regions. A reduction to 0.12 m^3/m^3 in volumetric soil moisture could severely constrain vegetation growth and further intensify drought stress across ecosystems and farming systems.

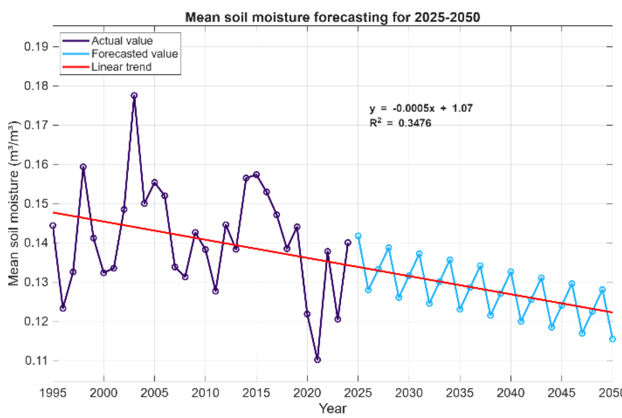

Figure 7. Actual and forecasted annual mean soil moisture values.

Such findings highlight the importance of adopting adaptive strategies in water and land resource management. Enhancing irrigation efficiency, promoting drought-resistant crop varieties and implementing soil moisture conservation practices (e.g., mulching, reduced tillage) may be necessary to maintain agricultural productivity under projected future conditions. Moreover, continuous satellite-based monitoring of soil moisture can serve as a crucial tool for early warning systems and policy planning in response to climate change and variability.

Figure 8 presents the observed annual mean precipitation values between 1995 and 2024, along with projections of annual means up to 2050 generated using the ARIMA model. As illustrated, the mean precipitation over the historical period was approximately 180 mm/year. Notably, the years 2002, 2003 and 2004 recorded values exceeding 220 mm/year, while in 1995, 2021 and 2023, the annual mean precipitation dropped to around 120 mm/year. The linear trend line in the figure indicates a slightly increasing trend in annual mean precipitation between 1995 and 2024. ARIMA-based projections suggest that this upward trend may continue, with annual average precipitation potentially reaching 220 mm/year by 2050.

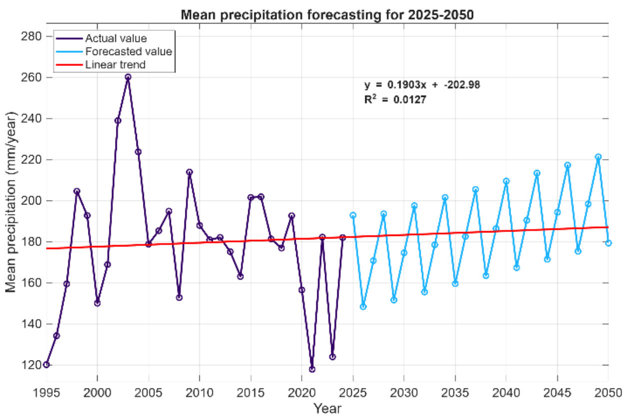

Figure 8. Actual and forecasted annual mean precipitation values.

This scenario may offer both opportunities and challenges for Uzbekistan's water and agricultural sectors. On one hand, increased precipitation can enhance water availability, support crop growth and alleviate drought pressure in certain regions. On the other hand, if precipitation increases are concentrated in shorter periods or come with more intense events, they could lead to soil erosion or inefficient water capture.

Therefore, while the forecasted increase in precipitation appears favourable, it must be interpreted alongside other climatic and hydrological indicators. Integrated water resource management and investment in water infrastructure (such as reservoirs and improved irrigation systems) will be essential to translate potential gains into sustainable outcomes for agriculture and ecosystems in Uzbekistan.

Table 1 summarizes the results of the Mann-Kendall test, which was applied to assess the statistical significance of the observed trends in key climate variables. The results revealed that evapotranspiration, LST and NDVI exhibited statistically significant increasing trends. This indicates that Uzbekistan has been experiencing rising surface temperatures and vegetation vigour, accompanied by an overall increase in evapotranspiration. Such trends are consistent with broader patterns of warming and potential vegetation stress, as higher LST and evapotranspiration rates can intensify water demand and potentially alter land cover characteristics.

Precipitation, although showing a slight upward trend, was not statistically significant according to the Mann-Kendall test. This suggests that, despite some variability or minor increases, there is no clear or persistent long-term trend in precipitation totals during the study period. This result implies that changes in water availability might not be driven primarily by shifts in precipitation alone, but rather by temperature-related processes affecting evapotranspiration and surface energy balance.

Soil moisture was the only parameter that showed a non-significant and decreasing trend. This downward tendency, although not statistically robust, may still signal emerging risks of soil drying, particularly when considered alongside the significant increases in temperature and evapotranspiration.

The Mann-Kendall test results point toward a warming and drying trajectory in Uzbekistan, characterized by increasing surface temperatures and evapotranspiration, but without a compensating increase in precipitation or soil water retention. These findings underscore the importance of climate adaptation strategies that address growing water stress and heat-related impacts in the region.

Climate parameter	p-value	Trend significant?
Evapotranspiration	0.0446	Yes
LST	0.0246	Yes
NDVI	0.0017	Yes
Soil Moisture	0.4118	No
Precipitation	0.6427	No

Table 1. Mann-Kendall test results (a significance level of α=0.05 was used to assess the statistical trends).

To evaluate the performance of the ARIMA model, the actual data from 1995 to 2024 were split into training and testing sets using a 70/30 ratio. The model was trained on the first 70% of the data and then used to estimate the remaining 30%, for which the coefficient of determination (R^2) was calculated. Among the studied variables, NDVI achieved the highest estimation accuracy with an R^2 of 0.64, followed by precipitation (0.54), LST (0.52), evapotranspiration (0.46) and soil moisture (0.44). While these results indicate that ARIMA can capture some temporal patterns, particularly for NDVI and precipitation, the moderate to low R^2 values suggest limitations in model performance. This underlines the need for longer time series and possibly additional explanatory variables to improve the robustness and accuracy of future projections.

4. Conclusion

This study analysed long-term trends of climate parameters, including evapotranspiration, LST, NDVI, soil moisture and precipitation, over Uzbekistan from 1995 to 2024. The Mann-Kendall test results indicated that trends in LST, NDVI and evapotranspiration were statistically significant, pointing to a warming climate and increased vegetative activity, whereas soil moisture and precipitation trends were not statistically significant. To extend the analysis into the future, the ARIMA model was employed to forecast these climate variables from 2025 to 2050. The ARIMA-based projections suggest that the climate conditions will be even more challenging for Uzbekistan by 2050. These results underscore the importance of proactive climate adaptation and land management strategies tailored to Uzbekistan's environmental conditions.

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