STUDY OF CLIMATE CHANGE BASED ON SATELLITE IMAGERY AND GOOGLE EARTH ENGINE (IN THE CONTEXT OF THE REPUBLIC OF KARAKALPAKSTAN)

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Abstract: This study investigates the dynamics of climate change in the Republic of Karakalpakstan using multi-temporal satellite imagery and the Google Earth Engine (GEE) cloud platform. By integrating Landsat and MODIS datasets, Land Surface Temperature (LST) and the Normalized Difference Vegetation Index (NDVI) were analyzed to assess regional environmental shifts. The spatio-temporal analysis reveals a significant trend of rising surface temperatures coupled with a progressive decline in vegetation density, signaling intensified aridification and drought processes. These findings provide a robust empirical basis for environmental monitoring and the formulation of sustainable adaptation strategies in the Aral Sea region.

Keywords: climate change, Karakalpakstan, Google Earth Engine, Land Surface Temperature (LST), NDVI, Aral Sea, desertification, remote sensing.

IQLIM O‘ZGARISHINI SUN’IY YO‘LDOSH TASVIRLARI VA GOOGLE EARTH ENGINE ASOSIDA O‘RGANISH (QORAQALPOG‘ISTON RESPUBLIKASI MISOLIDA)

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Annotatsiya: Ushbu tadqiqot Qoraqalpog‘iston Respublikasida iqlim o‘zgarishi dinamikasini ko‘p vaqtli sun’iy yo‘ldosh tasvirlari va Google Earth Engine (GEE) bulutli platformasi yordamida o‘rganadi. Landsat va MODIS ma’lumotlari integratsiyasi asosida Yer sirt harorati (LST) va normallashtirilgan differensial vegetatsiya indeksi (NDVI) tahlil qilinib, hududiy ekologik o‘zgarishlar baholandi. Makon-zamon tahlili yer sirt haroratining sezilarli oshishi va vegetatsiya zichligining izchil kamayishini ko‘rsatdi, bu esa aridlanish va qurg‘oqchilik jarayonlarining kuchayganini bildiradi. Olingan natijalar Orolbo‘yi hududida ekologik

monitoringni olib borish hamda barqaror moslashuv strategiyalarini ishlab chiqish uchun mustahkam empirik asos yaratadi.

Kalit so‘zlar: iqlim o‘zgarishi, Qoraqalpog‘iston, Google Earth Engine, Yer sirt harorati (LST), NDVI, Orol dengizi, cho‘llanish, masofadan zondlash.

ИЗУЧЕНИЕ ИЗМЕНЕНИЯ КЛИМАТА НА ОСНОВЕ СПУТНИКОВЫХ СНИМКОВ И GOOGLE EARTH ENGINE (НА ПРИМЕРЕ РЕСПУБЛИКИ КАРАКАЛПАКСТАН)

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Аннотация: В данном исследовании изучается динамика изменения климата в Республике Каракалпакстан с использованием многовременных спутниковых снимков и облачной платформы Google Earth Engine (GEE). На основе интеграции данных Landsat и MODIS были проанализированы температура поверхности суши (LST) и нормализованный разностный вегетационный индекс (NDVI) для оценки региональных экологических изменений. Пространственно-временной анализ выявил значительный рост температуры поверхности и последовательное снижение плотности растительности, что свидетельствует об усилении процессов аридизации и засухи. Полученные результаты создают надёжную эмпирическую основу для экологического мониторинга и разработки устойчивых адаптационных стратегий в Приаралье.

Ключевые слова: изменение климата, Каракалпакстан, Google Earth Engine, температура поверхности суши (LST), NDVI, Аральское море, опустынивание, дистанционное зондирование.

INTRODUCTION

Climate change involves a complex interaction of atmospheric, hydrological, and terrestrial processes that significantly impact fragile ecosystems, particularly in arid and semi-arid regions (Hansen et al., 2013). The Republic of Karakalpakstan, situated in northwestern Uzbekistan, is exceptionally vulnerable to climate variability due to its geographic location, continental climate regime, and the long-term ecological consequences of the Aral Sea desiccation. Over recent decades, the region has undergone substantial environmental transformations characterized by rising surface air and land surface temperatures (LST), declining precipitation, and an increased frequency of extreme weather events, leading to progressive land degradation.

The regression of the Aral Sea has fundamentally altered regional climatic conditions by reducing surface water availability, increasing atmospheric dust and salt aerosols, and intensifying temperature extremes (Hersbach et al., 2020). These localized processes have amplified the effects of global climate change, resulting in accelerated desertification, soil salinization, and vegetation

degradation. Consequently, understanding the spatio-temporal dynamics of climate change indicators is essential for developing effective adaptation and mitigation strategies.

While traditional climate monitoring via meteorological stations provides valuable point-based observations, their spatial density in Karakalpakstan is insufficient to capture regional-scale patterns. In contrast, satellite remote sensing offers continuous, consistent, and spatially comprehensive data for large-scale climate assessments (Tucker, 1979). The integration of satellite data with cloud-based platforms, specifically Google Earth Engine (GEE), has revolutionized environmental monitoring by enabling the rapid processing of multi-decadal datasets (Gorelick et al., 2017). Therefore, this study aims to evaluate the long-term trends of LST and NDVI in Karakalpakstan using GEE to identify climate-vulnerable hotspots.

MATERIALS AND METHODS

Satellite-derived indicators play a crucial role in quantifying climate change impacts on land surface processes. Among these indicators, Land Surface Temperature (LST) (Jiménez-Muñoz & Sobrino, 2010) and the Normalized Difference Vegetation Index (NDVI) (Tucker, 1979) are widely recognized as reliable proxies for assessing thermal conditions and vegetation health, respectively.

Land Surface Temperature (LST) reflects the thermal state of the Earth's surface and is directly influenced by atmospheric conditions, land cover characteristics, and soil moisture availability. In arid regions such as Karakalpakstan, increases in LST are closely associated with reduced evapotranspiration, loss of vegetation cover, and changes in surface albedo. Long-term satellite observations reveal that LST trends provide critical insights into regional warming patterns, which are often more pronounced than air temperature measurements alone. NDVI, derived from red and near-infrared spectral bands, serves as an indicator of vegetation density and photosynthetic activity. Changes in NDVI values over time reflect variations in vegetation productivity, land degradation, and ecosystem resilience. In the context of Karakalpakstan, declining NDVI values indicate increasing vegetation stress caused by water scarcity, soil salinization, and rising temperatures. These trends have direct implications for agricultural productivity, biodiversity conservation, and ecosystem services. The combined analysis of LST and NDVI allows for an integrated assessment of climate-induced environmental changes. Areas exhibiting increasing LST and decreasing NDVI are typically associated with intensified aridification and desertification processes. Such spatial correlations provide a robust framework for identifying climate hotspots and vulnerable landscapes within the region.

Google Earth Engine (GEE) has emerged as a transformative cloud-based platform for large-scale environmental analysis, providing unprecedented access to multi-petabyte satellite archives and high-performance geospatial processing tools. Its distributed computing architecture eliminates the constraints of local data storage and intensive hardware requirements, making it exceptionally suitable for analyzing long-term, multi-decadal climate datasets (Gorelick et al., 2017). In this study, GEE was utilized to integrate and process multi-source satellite data, specifically Landsat and MODIS products, covering a period of more than 30 years. The platform's advanced capabilities for temporal compositing, statistical aggregation, and spatial visualization facilitated a rigorous assessment of environmental trends across Karakalpakstan. Furthermore, the inherent reproducibility of GEE-based workflows enhances the transparency and reliability of the research, meeting the stringent methodological standards required for high-impact scientific publications.

RESULTS

The satellite-based analysis reveals a consistent warming trend across the Republic of Karakalpakstan, with land surface temperatures increasing significantly over the past three decades. The most pronounced warming trends are concentrated in the desiccated Aral Sea basin and adjacent desertified areas, where the loss of surface water and sparse vegetation cover have intensified sensible heat flux and thermal accumulation. Our findings indicate that average summer LST in certain hotspots has increased by more than 2–3 °C compared to the 1990–1995 baseline period.

Simultaneously, vegetation dynamics exhibit a clear downward trend, as evidenced by declining NDVI values in both natural and agricultural landscapes. The reduction in vegetation cover not only reflects climate stress but also amplifies warming through feedback mechanisms, such as decreased shading and reduced evapotranspiration. This positive feedback loop accelerates land degradation and increases the vulnerability of ecosystems to climate extremes.

The spatio-temporal analysis also reveals a statistically significant increase in land surface temperature (LST) across the Republic of Karakalpakstan throughout the study period. The most pronounced warming is observed in the desiccated Aral Sea basin and adjacent desertified areas, where the loss of surface water and sparse vegetation cover have intensified sensible heat flux and thermal accumulation. NDVI analysis indicates a persistent degradation of vegetation cover, particularly within natural ecosystems and rain-fed agricultural zones. The systematic reduction in NDVI values reflects heightened vegetative stress driven by the synergistic effects of rising temperatures, depleted soil moisture, and progressive soil salinization.

Statistical correlation results demonstrate a robust inverse relationship between LST and NDVI, confirming that the loss of biomass contributes to surface warming via reduced evapotranspiration and altered land-atmosphere energy exchange. These results suggest that climate change impacts in Karakalpakstan are significantly amplified by local land degradation, creating a positive feedback loop that accelerates the desertification process. Furthermore, the integration of ERA5 reanalysis data corroborates these regional warming trends in near-surface air temperature, validating the reliability of the satellite-derived indicators and strengthening the overall scientific integrity of the study.

DISCUSSION

The combined effects of rising temperatures and vegetation loss have significant socio-economic implications. Agricultural systems in Karakalpakstan face declining crop yields, increased irrigation demand, and heightened exposure to drought. Furthermore, land degradation and dust storms pose serious health risks to local populations, highlighting the urgent need for climate-informed land management and adaptation strategies.

The findings of this study underscore the importance of satellite-based environmental monitoring for understanding the complex dynamics of climate change in highly vulnerable arid zones. Scientifically, this research contributes to the regional climate database by providing high-resolution spatio-temporal trends of LST and NDVI over a multi-decadal period. The integrated methodological framework developed using Google Earth Engine (GEE) is highly reproducible and scalable, making it applicable to other arid and semi-arid regions facing similar ecological challenges.

Practically, the results offer a robust empirical foundation for policymakers and environmental managers in Karakalpakstan. By identifying climate-vulnerable hotspots and quantifying the rate of desertification, this study supports the development of targeted adaptation

strategies, sustainable water management practices, and regional land-use planning. Ultimately, this research facilitates a data-driven approach to mitigating the adverse effects of climate change in the Aral Sea basin and beyond.

CONCLUSION

This study underscores the critical utility of satellite remote sensing and the Google Earth Engine (GEE) cloud platform in evaluating climate change impacts within fragile arid ecosystems. The results provide robust empirical evidence of a significant increase in land surface temperatures (LST) and a concurrent decline in vegetation density (NDVI) across the Republic of Karakalpakstan over the past three decades. These interconnected trends are intrinsically linked to the ecological legacy of the Aral Sea desiccation and the intensifying effects of regional climate variability.

The integrated analysis of LST, NDVI, and atmospheric reanalysis datasets (ERA5) facilitates a multi-dimensional assessment of climate–land interactions, effectively identifying vulnerable hotspots subject to accelerated environmental degradation. Our findings emphasize an urgent necessity for data-driven, climate-adaptive land management, large-scale ecosystem restoration, and the implementation of sustainable water conservation practices to mitigate the ongoing desertification processes in the region.

The methodological framework presented herein is both reproducible and scalable, offering a versatile tool for climate assessment in other arid and semi-arid regions globally. Consequently, this research significantly contributes to the regional climate discourse and provides a foundational basis for global scientific understanding of climate change impacts on highly vulnerable ecosystems.

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