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MONITORING CLIMATE DYNAMICS AND CRYOSPHERIC CHANGES IN UGAM CHATKAL NATIONAL PARK, UZBEKISTAN: A REMOTE SENSING AND GIS-BASED ANALYSIS

ABSTRACT

Ugam-Chatkal National Park, a vital ecological region in Uzbekistan, is undergoing significant climate-driven changes, particularly affecting its cryosphere and seasonal snow cover. These changes pose serious environmental challenges, impacting water resources, biodiversity, and ecosystem stability. This study employs remote sensing and GIS techniques to analyze the mean annual temperature dynamics, glacier melting intensity, and Normalized Difference Snow Index (NDSI) variations from 2000 to 2024. ERA5 reanalysis data was utilized to assess temperature trends and glacier melt intensity, while Landsat-8 imagery was employed for NDSI calculations, providing insights into seasonal snow cover fluctuations. The results reveal a noticeable warming trend, with a corresponding increase in glacier retreat and a decline in snow-covered areas. Notably, glaciers in the northern parts of Ugam-Chatkal have melted significantly over the past four years, with melting intensity increasing considerably each year. This accelerated glacier retreat directly correlates with rising temperatures and declining snow cover, emphasizing the vulnerability of the region's high-altitude ecosystems. The study demonstrates the effectiveness of Google Earth Engine (GEE) as a powerful platform for large-scale environmental analysis, enabling rapid processing of multi-temporal satellite data. The use of GEE significantly reduces processing time, making it an efficient tool for climate impact assessments. These findings highlight the urgent need for enhanced conservation strategies and sustainable management approaches to mitigate the adverse effects of climate change on Central Asia's high-mountain ecosystems. This research contributes to a deeper understanding of climate-induced cryospheric changes and provides valuable insights for policymakers and environmental conservation initiatives.

KEYWORDS: Landsat, Ugam-Chatkal National Park, glacier melting, Normalized Difference Snow Index (NDSI), climate change, cryosphere monitoring

INTRODUCTION

Climate change has emerged as one of the most pressing global environmental challenges, significantly impacting high-mountain ecosystems [*Gafforov* et al., 2020; *Didovets* et al., 2021;

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Kulmatov, *Khasanov*, 2023; *Avezov* et al., 2024]. Rising temperatures, accelerating glacier retreat, and decreasing snow cover threaten water resources, biodiversity, and ecological stability. Mountainous regions, such as Ugam-Chatkal National Park in Uzbekistan, are particularly vulnerable due to their dependence on seasonal snow and glacial meltwater [*Alikhanov* et al., 2024; *Juliev* et al., 2024].

Understanding the dynamics of these environmental changes is crucial for sustainable resource management and climate adaptation strategies. Climate change is exerting unprecedented pressure on the cryosphere of Central Asia, leading to accelerated glacier retreat, reduced snow cover, and altered hydrological regimes. In the Ugam-Chatkal National Park — one of Uzbekistan's most critical high-altitude protected areas — these changes threaten the sustainability of water resources, biodiversity, and ecosystem services that support both local communities and downstream regions. Despite the park's ecological and hydrological significance, systematic assessments of recent cryospheric changes remain scarce, and there is limited understanding of how temperature dynamics are driving glacier melt and snow cover reduction at a multi-year scale. This lack of localized, high-resolution climate and cryosphere monitoring hampers the development of targeted adaptation and conservation strategies. Without timely scientific evidence, the region faces increasing risks of water scarcity, biodiversity loss, and ecological imbalance. Therefore, there is an urgent need to quantify and monitor climate-driven cryospheric changes in Ugam-Chatkal National Park using advanced remote sensing and cloud-based GIS technologies to inform effective environmental management policies [*Alikhanov* et al., 2020; *Alikhanov* et al., 2021]. The park is home to diverse flora and fauna, including several endangered species that rely on stable climatic conditions [*Beshko* et al., 2023; *Bronzes* et al., 2025]. Glacial retreat and declining snow cover in the park directly affect regional water resources, making its study imperative for sustainable environmental management [*Barbier* et al., 2011; *Wu* et al., 2025]. The findings of this research can inform national policies on climate adaptation, water resource management, and conservation planning.

Globally, numerous studies have highlighted the effects of climate change on mountainous regions. Research in the Himalayas [*Panda*, 2022] and the Alps [*Beer* et al., 2024] has demonstrated that rising temperatures are leading to significant glacier mass loss and alterations in seasonal snow patterns. Similarly, studies in the Tien Shan Mountains [*Zhou* et al., 2021] have revealed a considerable reduction in glacier volume, impacting regional water availability.

In Central Asia, research by Kutuzov and Shahgedanova [*Kutuzov* et al., 2013] has provided evidence of glacier retreat trends, emphasizing the need for continuous monitoring. Despite these advancements, studies focusing on Uzbekistan's mountain ecosystems remain scarce, making this research highly relevant for national environmental policies. The use of remote sensing and cloud computing platforms such as Google Earth Engine (GEE) has revolutionized climate-related studies, enabling large-scale analysis of land surface changes over time [*Aslanov* et al., 2021; *Arpitha* et al., 2023]. ERA5 reanalysis data provides high-resolution temperature and glacier melt data, facilitating climate trend assessments. Meanwhile, Landsat-8 imagery is widely used for monitoring snow cover through the Normalized Difference Snow Index (NDSI), offering valuable insights into seasonal variations and long-term trends [*Abdulkadhim*, 2019; *Wang* et al., 2022; *Mukherjee*, *Krishna*, 2023].

Glacier melting is primarily driven by variations in air temperature, solar radiation, and precipitation patterns. Rising mean annual temperatures accelerate ice ablation, reduce accumulation rates, and shift the snowline to higher elevations [*Hock*, 2022; *Vandecrux* et al., 2023]. These processes not only diminish glacier volume but also alter runoff regimes, potentially leading to seasonal water shortages. According to mountain climatology theory, small glaciers in continental climates are particularly sensitive to temperature anomalies, exhibiting rapid mass balance changes in response to even minor climatic fluctuations. Snow cover dynamics are another key component of cryospheric studies [*Collins*, 1990; *De Kok* et al., 2020]. The Normalized Difference Snow Index (NDSI), based on the high reflectance of snow in the visible spectrum (Green band) and strong absorption in the shortwave infrared (SWIR), is a widely accepted remote sensing method for identifying snow-covered areas [*Hall*, *George*, 2010].

In climate science, reanalysis datasets such as ERA5 integrate satellite observations, ground-based measurements, and numerical weather prediction models to produce consistent, multi-decadal climate records [*Draeger* et al., 2024]. The ERA5 2m air temperature product provides a theoretical basis for assessing surface-level thermal conditions that directly influence glacier and snow melt rates. Similarly, snow depth and precipitation parameters from reanalysis data are valuable for understanding seasonal accumulation and melt patterns. Remote sensing and Geographic Information Systems (GIS) provide the methodological framework for monitoring cryospheric changes [*Braithwaite*, *Hughes*, 2020]. The theoretical advantage of using cloud-based platforms like Google Earth Engine lies in their ability to process multi-temporal, multi-source datasets rapidly, enabling continuous and scalable environmental monitoring [*Amani* et al., 2020; *Zhao* et al., 2021]. This aligns with the principle of synoptic observation in earth sciences, where spatially consistent and temporally frequent measurements are crucial for detecting environmental change trends.

While previous studies have examined glacier retreat and snow cover changes in the Tien Shan and other Central Asian Mountain systems, there has been limited research specifically focusing on the Ugam-Chatkal National Park in Uzbekistan over recent years. This study provides a novel contribution by integrating ERA5 reanalysis climate data and Landsat-8 OLI imagery within a Google Earth Engine (GEE) cloud-computing framework to analyze cryospheric dynamics from 2021 to 2024 — a period characterized by accelerated climate change impacts in the region. The originality of this research lies in:

1. Conducting a multi-indicator assessment (temperature trends, glacier melt intensity, and NDSI-based snow cover change) for a UNESCO-listed protected area in Uzbekistan, where such integrated analyses are scarce.
2. Applying time-specific seasonal analysis (days 60–180) to capture the critical snowmelt and glacier melt periods, enhancing the temporal precision of climate impact monitoring.
3. Demonstrating the practical advantages of GEE for rapid cryosphere monitoring in data-limited mountainous regions, offering a replicable workflow for other high-altitude protected areas.

These elements not only supplement existing research but also provide region-specific insights essential for climate adaptation and conservation strategies in Central Asia's high-mountain ecosystems.

RESEARCH MATERIALS AND METHODS

Ugam-Chatkal National Park is a protected natural reserve located in the northeastern part of Uzbekistan, within the Tashkent Region. The park is part of the Western Tien Shan Mountain Range, which extends across Uzbekistan, Kazakhstan, and Kyrgyzstan. It is a key conservation area, designated as a UNESCO World Heritage Site, due to its unique biodiversity, pristine landscapes, and ecological significance. Ugam-Chatkal National Park covers approximately 575 000 ha, stretching across several districts of the Tashkent Region, including Bostanlyk and Parkent. The park's terrain is dominated by rugged mountains, deep valleys, and high-altitude plateaus, with elevations ranging from 900 meters to over 4 200 meters above sea level. The highest peaks, such as Greater Chimgan (3 309 m) and Big Chimgan (3 300 m), are crucial landmarks in the region.

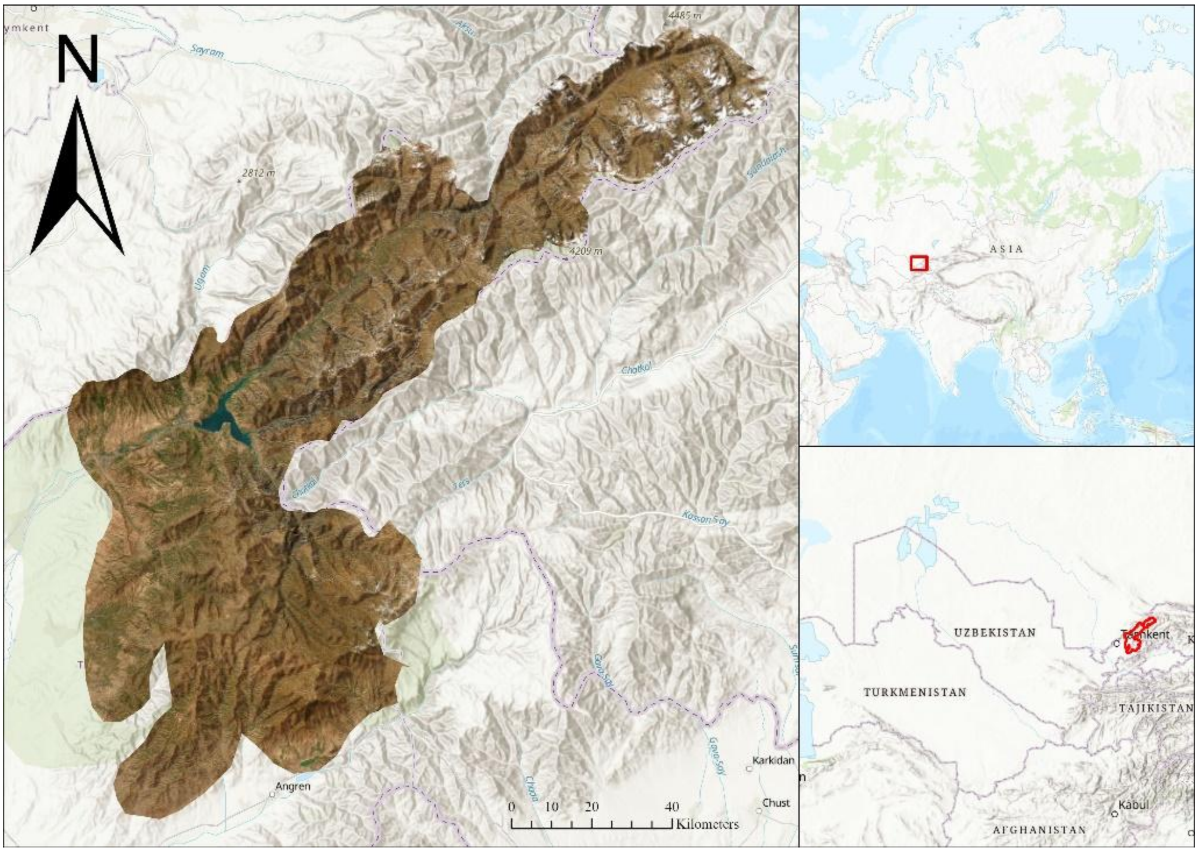

Fig. 1. The study area location map

The park is bordered by The Pskem and Chatkal mountain ranges to the east and south, The Ugam range to the north, Kazakhstan's Sairam-Ugam National Park to the northwest. This geographical setting makes Ugam-Chatkal an essential hydrological and ecological corridor within Central Asia. The climate of Ugam-Chatkal National Park is classified as continental mountainous, characterized by Cold winters (average temperatures: −10 °C to −15 °C at high altitudes), mild to hot summers (average temperatures: 15 °C to 30 °C in lower valleys), heavy seasonal precipitation, mostly occurring as snowfall in winter and rain in spring and autumn. Due to its high elevation, the park experiences significant temperature variations, influencing glacier melt rates and seasonal snow cover. Over recent years, rising temperatures and decreasing precipitation trends have led to accelerated glacier retreat and reduced snow persistence, affecting water availability in the region.

Ugam-Chatkal National Park is home to diverse ecosystems, ranging from alpine meadows and coniferous forests to glacial landscapes and high-altitude deserts. It hosts rare and endemic species, including snow leopards (*Panthera uncia*) — an endangered species, Tian Shan brown bears (*Ursus arctos isabellinus*), golden eagles (*Aquila chrysaetos*), wild mountain goats (*Capra sibirica*). The park's biodiversity is closely linked to climatic conditions and hydrological stability, making climate change a major threat to its ecosystem integrity [*Sulaymonov* et al., 2019; *Juliev* et al., 2024].

Data sources

In this study, we utilized two different satellite datasets, ERA5 and Landsat-8, which differ in spatial resolution, spectral characteristics, and technical parameters, allowing for a comprehensive analysis of temperature dynamics, glacier melting, and snow cover changes. Below are the band names and descriptions for ERA5 used for mean annual temperature and glacier melting analysis and Landsat-5/8 OLI/TIRS bands.

The Normalized Difference Snow Index (NDSI) is a remote sensing-based index used to detect and monitor snow cover. It differentiates snow from clouds, water, and vegetation by utilizing the strong reflectance of snow in the visible Green band and its strong absorption in the Shortwave Infrared [*Hall* et al., 1995; *Salomonson*, *Appel*, 2004]. [*Salomonson*, *Appel*, 2004] further validated NDSI using MODIS data and highlighted its effectiveness for large-scale, operational monitoring of snow cover extent. Today, NDSI (1) is considered the standard snow cover detection index, forming the basis of multiple snow-related climate and hydrological studies.

$$NDSI = \frac{(Green - SWIR1)}{(Green + SWIR1)} \quad (1),$$

where *Green* — Landsat-5 TM Band 2 (0.52–0.60 μm) and Landsat-8 OLI Band 3 (0.53–0.59 μm), *SWIR1* — Landsat-5 TM Band 5 (1.55–1.75 μm) and Landsat-8 OLI Band 6 (1.57–1.65 μm).

RESEARCH RESULTS AND DISCUSSION

This study analyzed the spatiotemporal dynamics of mean annual temperature, glacier melting intensity, and normalized snow index (NDSI) in Ugam-Chatkal National Park from 1960 to 2024 using remote sensing and GIS-based techniques. Google Earth Engine (GEE) was employed for large-scale data processing, integrating ERA5 reanalysis data for temperature and glacier melting analysis, and Landsat-5/8 OLI/TIRS imagery for NDSI computation.

ERA5-derived monthly air temperature data from 1960 to 2024 reveal a gradual but consistent warming trend across the study area. Although interannual variability is clearly visible, the regression line indicates an upward trajectory in mean temperature. The year 2024 registered among the highest mean annual temperatures in the entire series, reflecting broader global warming patterns impacting high-altitude ecosystems. This persistent warming provides a primary driver of enhanced glacier melting and snow cover reduction (Fig. 2).

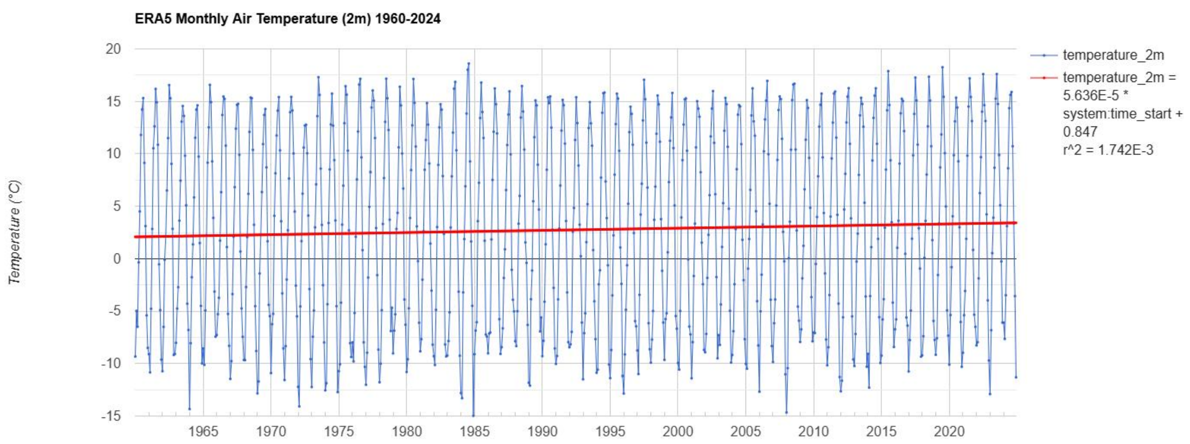

Fig. 2. Monthly air temperature trends (2 m) in Ugam-Chatkal National Park from 1960 to 2024 based on ERA5 reanalysis data. The blue line represents monthly variations, while the red line indicates the long-term linear trend, showing a gradual warming pattern over the study period

The glacier melt dynamics highlight distinct differences between 1960, 2000, and 2024. In 1960, snowmelt initiation was relatively delayed and stable, with negligible fluctuations until approximately the 100th day of the year. Melting accelerated steadily only after this point, following a consistent seasonal pattern. In contrast, the year 2024 displayed markedly unstable dynamics: multiple peaks of intensive snow and ice melting occurred well before the 100th day of the year, reflecting premature thawing episodes. These irregular melt pulses indicate the destabilizing influence of rising temperatures and climatic variability. The year 2000 shows intermediate behavior, with earlier melt onset compared to 1960, but less volatility than 2024 (Fig. 3).

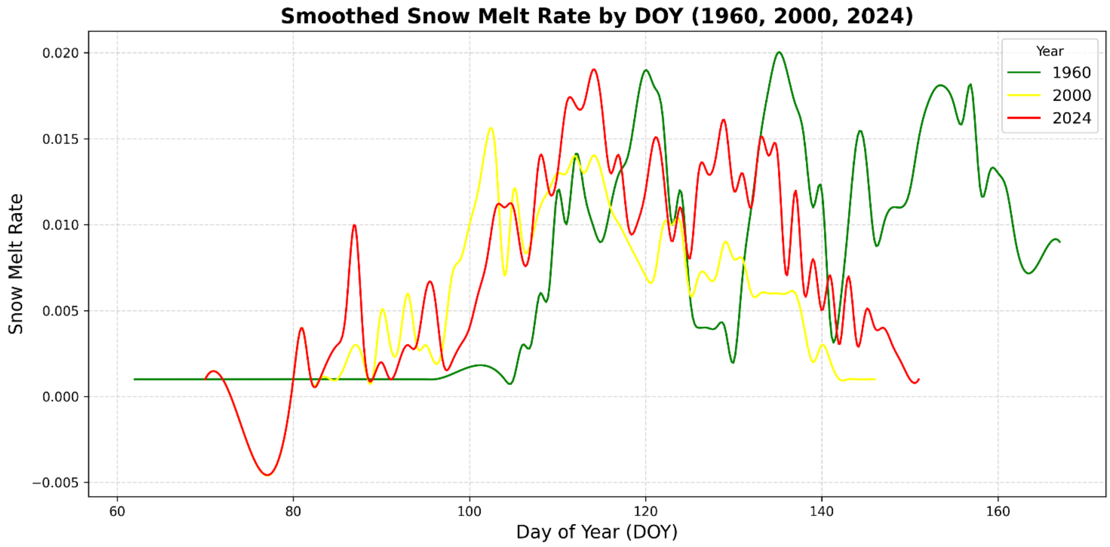

Fig. 3. Smoothed (with Savitzky-Golay Filter) snowmelt rate by day of year (DOY) for 1960, 2000, and 2024. The 1960 curve shows stable melt dynamics until approximately DOY 100, while 2000 indicates an earlier onset of melting. In 2024, melt dynamics are highly unstable, with multiple intensive melt events occurring before DOY 100, highlighting the influence of rising temperatures and climatic variability

The figure illustrates the temporal dynamics of the Normalized Difference Snow Index (NDSI) across different years within the early melt season (DOY 60–180) (Fig. 4).

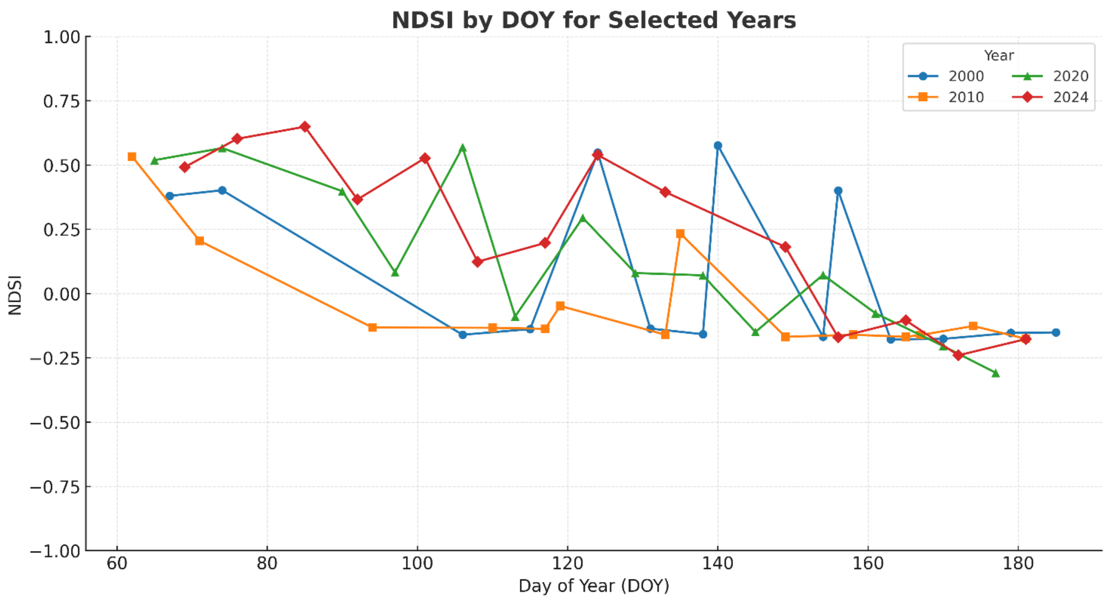

Fig. 4. Seasonal dynamics of the Normalized Difference Snow Index (NDSI) across different years (2000, 2010, 2020, and 2024). The line chart illustrates day-of-year (DOY) variations, highlighting interannual differences in snow cover extent and timing. Peaks and troughs represent seasonal accumulation and melting phases, while comparative shifts across years indicate long-term variability in snow cover conditions

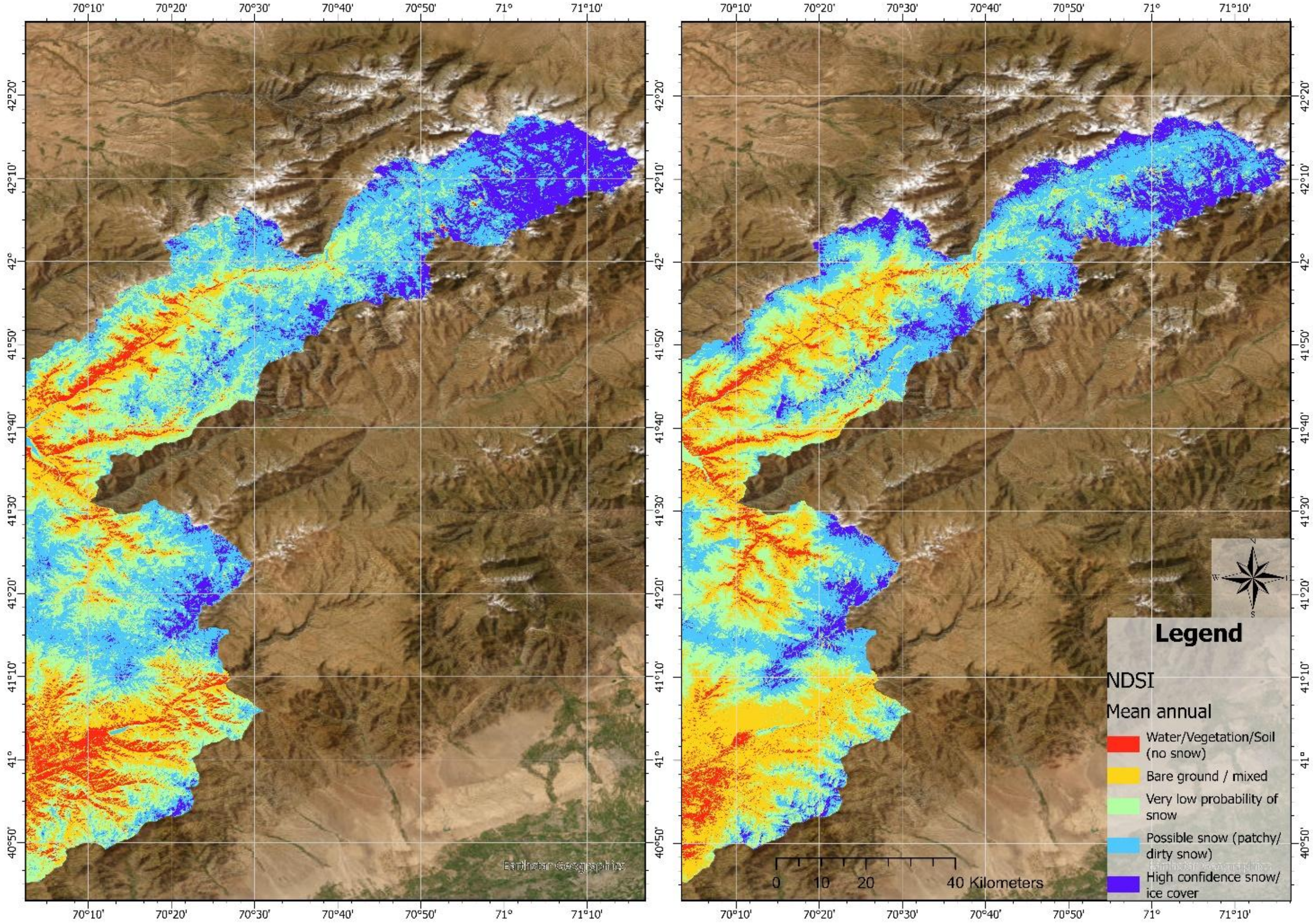

Fig. 5. Comparison of annual mean NDSI maps for the study area between 2000 (left) and 2024 (right), illustrating the spatial distribution and temporal changes in snow and ice cover over the two decades

In 2000 (blue), NDSI values show a gradual decline from ~0.4 in early March to negative values by late June, reflecting a relatively steady and delayed snowmelt process. In contrast, 2010 (orange) exhibits consistently lower NDSI values (<0.25 after DOY 80), indicating an earlier onset of snowmelt and reduced snow persistence compared to 2000. By 2020 (green), NDSI values initially remain higher (~0.5–0.6 in March), but decline sharply around DOY 100–120, suggesting intensified and more rapid melting episodes. The 2024 (red) curve highlights pronounced fluctuations, with NDSI exceeding 0.6 in early March but dropping irregularly throughout the season, indicating unstable snow cover conditions and multiple melt pulses.

The mean annual NDSI maps illustrate clear spatial changes in snow cover and glacier extent between the two study years (Fig. 5). In the earlier year (left map), high-confidence snow and ice cover (dark blue) dominate the upper mountainous regions, while mid-elevation areas retain a mixture of patchy snow and bare ground. By contrast, the more recent year (right map) shows a substantial reduction in continuous snow cover, with many zones transitioning from stable snow and ice to patchy or dirty snow (light blue) and bare ground/vegetation (orange to red). This shift is most pronounced along the central and northern ridges, where glaciers have retreated, and snow cover persistence has declined. The expansion of bare surfaces highlights intensified melting processes, while the contraction of snow-dominated areas underscores reduced seasonal accumulation. Overall, the comparison provides strong evidence of accelerated glacier melting and diminished snow cover in the region, consistent with warming temperature trends derived from ERA5 data.

CONCLUSIONS

This study highlights the accelerating impacts of climate change on snow and glacier dynamics in the Ugam-Chatkal National Park Region. Analysis of ERA5 reanalysis data revealed a significant warming trend from 1960 to 2024, with particularly high mean annual temperatures observed in the most recent decade. These rising temperatures are directly linked to intensified glacier melting and reduced snow cover persistence.

The Landsat-derived Normalized Difference Snow Index (NDSI) further confirmed these findings. Comparison of annual mean NDSI maps between 2000 and 2024 showed a substantial reduction in high-confidence snow and ice cover, accompanied by an expansion of bare ground and vegetation zones. Temporal analysis of NDSI by day of year (DOY) demonstrated earlier onset of snowmelt and unstable seasonal snow dynamics in 2024 compared to more stable patterns in 2000.

Overall, the integration of multi-source datasets provided robust evidence of snow cover decline and glacier retreat in the study area. These results underscore the urgent need for continued monitoring and adaptation strategies to mitigate the ecological and hydrological consequences of accelerated cryospheric change.

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