

Article

Climate-Driven Snow Cover Dynamics in the Hindu Kush–Himalayan (HKH) Region and Its Implications for Natural Hazard Modeling Using Multi-Satellite Hydrometeorological Data

Muhammad Amin ¹, Sikandar Ali ^{2,3}, Muhammad Safdar ⁴, Taixia Wu ⁵, Muhammad Farhan ⁵, Moazzam Mushtaq ², Zeyang Song ⁴, Xining Liu ⁶, Hongzhao Tang ⁷ and Adnan Arshad ^{8,*}

¹ Institute of Geo-Information & Earth Observation, PMAS Arid Agriculture University, Rawalpindi 46300, Pakistan; m.amin@uaar.edu.pk

² Department of Irrigation and Drainage, Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad 38000, Pakistan; sikandar_ali@uaf.edu.pk (S.A.); 2018ag7891@uaf.edu.pk (M.M.)

³ NCGSA-Agricultural Remote Sensing Laboratory, University of Agriculture, Faisalabad 38000, Pakistan

⁴ College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; m.safdar@xust.edu.cn (M.S.); zeyang.song@xust.edu.cn (Z.S.)

⁵ School of Earth Sciences and Engineering, Hohai University, Nanjing 210098, China; wutx@hhu.edu.cn (T.W.); m.farhan@hhu.edu.cn (M.F.)

⁶ Sanya Institute of South China Sea Geology, Guangzhou Marine Geological Survey, China Geological Survey, Sanya 572024, China; liuxining@mail.cgs.gov.cn

⁷ Land Satellite Remote Sensing Application Center, Ministry of Natural Resources of China, Beijing 100048, China; tanghz@pku.edu.cn

⁸ State Key Laboratory of Grassland Agro-Ecosystem, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730020, China

* Correspondence: ad@cau.edu.cn

Abstract

Earth's frozen water reserves are inherently dynamic and play a critical role in the hydrological processes of complex, dynamic river basins. Climate-driven environmental changes have led to a significant decrease in the area and duration of seasonal snow cover, particularly in the high-altitude Asian Water Tower (Himalaya). Snow cover estimates are challenging in the high-altitude Hindu Kush-Himalayan (HKH) region, which is a core contributor to water resources that sustain the environment and diverse downstream ecosystems that support more than half of the Earth's population. This study quantifies the snow cover area over the period of 1993–2023 across the basins of ten major snow- and rainfall-dominated rivers in the HKH region using Landsat-based Normalized Difference Snow Index (NDSI), SNOMAP, Blue Snow Threshold (BST), and Dozier and Painter methods. Additionally, this study used 178 strategically positioned points across the HKH region to explore the relationship between snow cover dynamics and environmental factors such as temperature, precipitation, and greenhouse gas concentrations. The study observed significant temporal and spatial variations in snow cover, driven by regional climatic conditions and anthropogenic influences. The results revealed declining snow cover trends of 2793.15, 2108.86, 1199.49, 247.51, 230.34, and 169.39 km²/year for the Amu Darya, Indus, Yangtze, Tarim, Mekong, Ganges, and Brahmaputra River basins, respectively. Conversely, the Salween, Yellow, and Irrawaddy River basins showed a slight increase of 1002.66, 147.06, and 20.86 km²/year, respectively. These opposing trends underline the vulnerability of snow mass to water supply and hydropower scheduling,

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stressing the urgent need for integrated, long-term satellite and ground-based observation platforms, as well as robust hydrological and glaciological modeling. A strategic blend of remotely sensed snow cover data and locally calibrated climate and land-use records will empower decision-makers to predict water security threats and refine reservoir operation guidelines, thereby sustaining both socio-economic and ecosystem services across the principal river corridors.

Keywords: snow cover; HKH; NDSI; Indus; Ganges; Yangtze; climate change; Landsat

1. Introduction

Snow, a crucial freshwater reservoir [1], plays an essential role in regulating the Earth's climate system [2], regulating inter-seasonal water supplies [3], changing regional weather patterns, and maintaining ecological stability [4]. The Hindu Kush-Himalayan (HKH) region is also known as the "Water Tower of Asia" [5], plays a critical role in sustaining the region's freshwater systems. These high-elevation zones function as vital water reserves, holding substantial quantities of freshwater in the form of snow and glacial ice. Often referred to as the "Third Pole," this region sustains the lives of approximately 210 million people by providing essential ecosystem services [6]. As climate change accelerates, understanding the dynamics of snow cover in regions such as the HKH, often termed the "Third Pole," is becoming increasingly critical [7]. The HKH region, home to many of the world's highest peaks and largest glaciers, is experiencing significant changes due to global warming [8]. Rising temperatures, driven by anthropogenic activities such as deforestation, fossil fuel combustion, and land-use changes, are altering snow and glacier accumulation and ablation patterns in this region [9]. Over the past century, the HKH region has warmed faster than the global average, with temperatures rising by more than 0.74 °C [10]. This warming threatens the stability of the cryosphere, leading to earlier snowmelt, shifting river discharge patterns, and ultimately reduced water availability during critical agricultural seasons [11]. This altered snowmelt pattern is of particular concern for densely populated regions downstream, where rivers fed by snowmelt serve as lifelines for millions of people [12].

Snowmelt contributes to river flows, providing surface water supplies downstream, recharging groundwater systems, and ensuring the continuity of agricultural productivity [13]. For instance, the Indus River, which sustains Pakistan's extensive agricultural landscapes and generates hydroelectric power, depends heavily on snowmelt from the HKH mountains [14]. This widespread reliance on mountain snowmelt highlights the need to monitor snow cover patterns and processes, especially as climate change continues to alter overall weather conditions [15]. Rising global temperatures and environmental changes are accelerating glacier melt and contributing to a steady annual decline in snow cover extent. In the HKH region, snow cover varies considerably across space and time, with seasonal changes largely driven by fluctuations in temperature and precipitation patterns [16] and broader atmospheric dynamics [17]. Shifts in atmospheric circulation linked to global warming are projected to influence precipitation patterns in the HKH region, potentially reshaping snow cover dynamics [18]. Continuous monitoring of cryospheric water reserves is essential for effective water resource management, evaluating climate change impacts and improving runoff prediction and freshwater planning.

Remote sensing technology has proven invaluable for monitoring snow cover trends [19], especially in hard-to-reach areas such as the Hindu Kush-Himalayan (HKH) mountain region. Collecting ground-based data in mountainous regions is often limited

by rugged landscapes, extreme weather and accessibility issues. Nonetheless, recent improvements in satellite technology and sensor resolution have greatly enhanced our capacity to monitor snow cover more accurately and across larger areas [19]. Since NASA's launch of the Landsat program in 1972, satellites like the Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and the more advanced Operational Land Imager (OLI) have played a key role in monitoring snow cover and analyzing its changes over time and space [20]. The Landsat-based NDSI, water and forest masking, and snow cover forest detection have significantly improved the accuracy of snow cover mapping [1]. These advancements have enabled researchers to gain deeper insights into snow cover extent and the factors influencing its variation over time [21]. Despite these advancements, accurately estimating snow cover using remote sensing remains challenging because of persistent issues such as cloud interference, dense vegetation, and the potential misclassification of water bodies. These factors can introduce uncertainty into snow cover assessments [22]. However, integrating time-series data from multiple satellite platforms, along with advanced modeling techniques, has enabled researchers to reduce these limitations and produce more consistent, detailed insights into snow cover dynamics [23].

Numerous studies have utilized different methods to estimate snow cover in different geographic settings, aiming to capture spatial and temporal variations in snow dynamics [24–27]. Quantifying snow cover changes in the HKH region remains complex due to its vast terrain, frequent cloud cover, atmospheric interference, and limitations in satellite resolution and data consistency. This study proposes a comprehensive approach using 4 methodologies to assess snow cover trends across the HKH region from 1993 to 2023, using Landsat imagery from Landsat 5 to Landsat 9. The primary objective is to analyze snow cover dynamics over 30 years across snow-dominated river basins in the HKH, which supply water to more than half of the world's population. The study also investigates the relationship between snow cover dynamics and temperature, precipitation, and greenhouse gases. The study addresses key remote sensing challenges, including cloud contamination, snow detection in forested areas, and the misclassification of water bodies. The findings will offer valuable insights into hydrological shifts in the HKH and support the development of adaptive resource management strategies to cope with the impacts of climate change on agriculture, hydropower, and the livelihoods of the millions dependent on snowmelt-fed systems.

2. Materials and Methods

2.1. Study Area

This study was conducted within the HKH region, which is shown in Figure 1. The Hindu Kush Himalaya (HKH) region extends roughly between 24° and 38° north latitude and 72° to 97° east longitude, covering a vast and diverse terrain across multiple South Asian countries. The Greater Himalayas are the origin of ten significant river systems in Asia, including the Amu Darya, Irrawaddy, Brahmaputra, Indus, Yellow, Ganges, Salween, Mekong, Yangtze, and Tarim rivers, collectively covering a substantial surface area of approximately 7×10^6 km² [28]. Covering an estimated area of 60,000 km², the HKH region is home to the world's largest expanse of land ice outside the polar regions [29]. This region plays a crucial role in providing ecosystem services, including agricultural diversity, water, and nutrients, to extensive arable lands in downstream river basins such as the Ganges, Indus, Brahmaputra, and others [30].

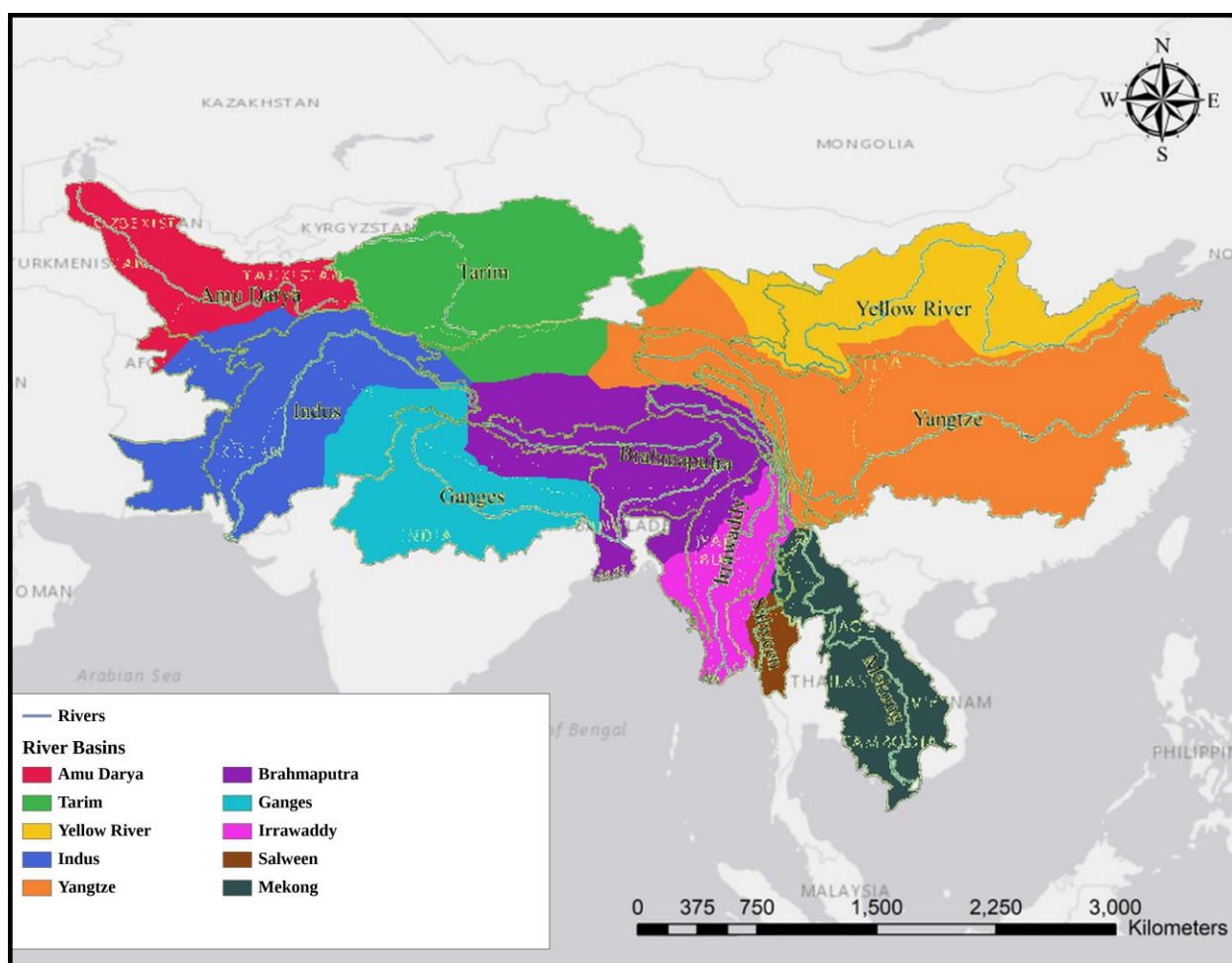


Figure 1. Topographic map of the HKH region and its snow-dominated river basins. The HKH region is outlined in dark green, with river basins shaded in light green. The snow-dominated rivers are illustrated as blue lines, highlighting their spatial distribution and hydrological importance.

The HKH region, which supports critical ecosystem services for more than one-third of the global population, faces a range of environmental challenges. These include land use and land cover changes, climate variability, and the spread of invasive species, all of which contribute to biodiversity loss and ecosystem degradation [31]. The mountainous terrain of the HKH region is highly vulnerable to climate change impacts. Between 1901 and 2014, the area experienced an average temperature increase of approximately 0.10 °C per decade [32]. In the 21st century, rising concentrations of atmospheric aerosols and black carbon emissions in the HKH region have accelerated warming, contributing to faster snowmelt across the mountains [33]. Due to its distinctive orography, rugged terrain, and monsoon-driven climate, the HKH region is highly prone to flooding associated with climate extremes. This susceptibility often results in severe and damaging flood events [34]. These changes can profoundly affect biodiversity and the livelihoods of local communities, particularly in the high-altitude regions of the Greater Himalayas [35].

Understanding the intricate relationship between snow cover dynamics and environmental factors, including temperature, precipitation, and greenhouse gas concentrations, 178 points were selected across 10 river basins within the HKH region, as shown in Figure 2, providing comprehensive coverage of the diverse landscapes and environmental conditions in the HKH region. These points are strategically spaced about 100 by 100 km apart, ensuring adequate representation across the region and capturing variations in terrain and climate. Within each basin, these points are subsequently indexed locally from 1 to n for that basin (e.g., 1–28 for the Amu Darya basin), where n is the

number of points lying in a specific basin depending on the basin's areal extent within the 100×100 km grid; this local numbering is used to label points in Figures 10–17.

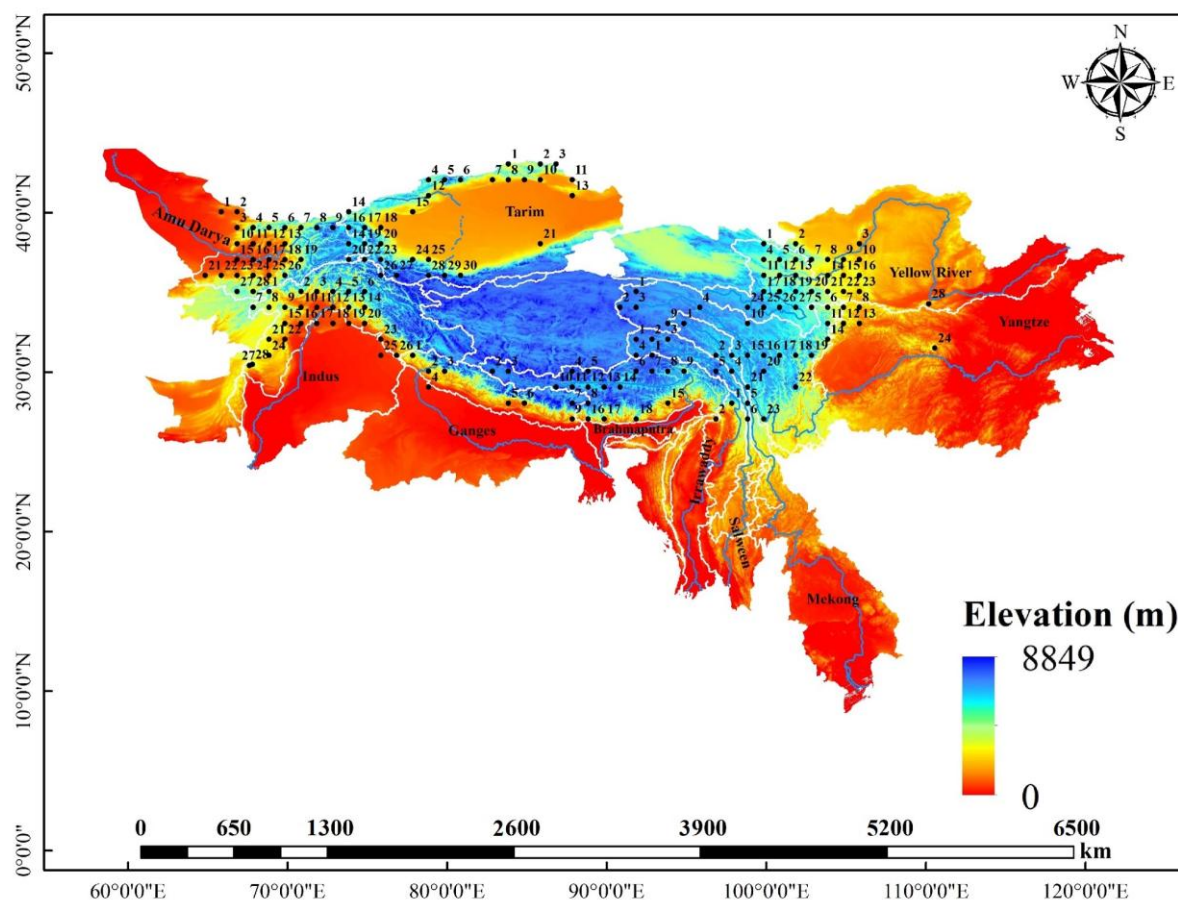


Figure 2. Spatial distribution of 178 selected points over the Tarim, Amu Darya, Indus, Yangtze, Yellow, Brahmaputra, Ganges, and Salween river basins.

2.2. Datasets Used in the Study

Utilizing the Google Earth Engine platform, Level 2 Collection 2 Tier 1 (T1_L2) datasets were acquired for each Landsat satellite within a specified future temporal range and geographical bounds. The selection process prioritized data quality, excluding scenes with high cloud cover. This study utilized data from Landsats 5, 7, 8, and the recently launched Landsat 9 to ensure consistent temporal coverage. Four Landsat missions contributed imagery to this study, each used over a specific sub-period of its operational archive rather than its full mission lifetime. Landsat 5 (TM sensor), operational from March 1984 to June 2013, contributed imagery from 1993–1999, providing essential surface reflectance data across multiple spectral bands at a 30-m resolution. Landsat 7 (ETM+ sensor), operational since April 1999, contributed imagery from 2000–2011, maintaining continuity in snow cover monitoring. Landsat 8 (OLI sensor), operational since February 2013, contributed imagery from 2012 onward, offering improved spectral and spatial capabilities. Landsat 9 (OLI-2 sensor), operational since September 2021, was added to the dataset from 2022, further strengthening the record by continuing observations with identical spectral bands and resolution and supporting long-term snow cover analysis. The year ranges reported above for each satellite indicate the imagery years used in this study and should not be interpreted as the satellites' full operational lifespans. These satellites, with their ability to capture imagery perpendicular to the Earth's surface and a 14-day revisit cycle, ensured reliable, continuous data acquisition and provided a robust

foundation for long-term environmental monitoring and remote sensing applications. Table 1 presents the datasets used in the study.

Table 1. Landsat datasets used in this study.

Satellite	Sensor	Period Covered	Number of Scenes	Spatial Resolution
Landsat 5	TM	1993–1999	N5	30 m
Landsat 7	ETM+	2000–2011	N7	30 m
Landsat 8	OLI	2013–2023	N8	30 m
Landsat 9	OLI-2	2022–2023	N9	30 m

To investigate the intricate relationship between snow cover dynamics, concentrations of greenhouse gases, temperature variations, and precipitation patterns, data were meticulously collected from the Copernicus Atmosphere Monitoring Service (CAMS; see <https://atmosphere.copernicus.eu/>, accessed on 15 October 2024), the CPC Global Unified 0.5×0.5 Daily Gridded Temperature, and the Global Precipitation Climatology Centre (GPCC). The GPCC data includes the GPCC Monthly Total Precipitation and GPCC Precipitation 0.25-degree V2020 Full Reanalysis, which provide high-resolution and comprehensive precipitation records essential for climate studies. CAMS, an essential part of the European Union's Earth observation Copernicus, began operations in July 2015. Managed by the European Centre for Medium-Range Weather Forecasts (ECMWF), CAMS embodies a genuine European endeavor with over 23,500 direct data users and more than 200 million end users worldwide as of March 2022. Drawing on ECMWF's Integrated Forecasting System (IFS) and utilizing over 90 different satellite data streams, CAMS provides diverse global and regional information products on air quality, greenhouse gases, solar energy, ozone and UV radiation, among others. Available at no cost through the Atmosphere Data Store, CAMS plays a pivotal role in furnishing comprehensive atmospheric data vital for scientific inquiry, policy formulation, and public awareness [36]. By leveraging CAMS data, along with data from the CPC Global Unified 0.5×0.5 Daily Gridded Temperature and GPCC's comprehensive precipitation records, scientists can elucidate the impacts of climate change, inform evidence-based policy decisions and raise public awareness of the pressing environmental challenges facing our planet.

2.3. Methodology

For each Landsat series, cloud-free snow cover composites were generated using Google Earth Engine using a moving compositing window of approximately 1 to 1.5 months, within which the least cloud-affected available scenes were selected. The time span and areas obscured by extensive cloud cover were excluded from the composite analysis. The length of this compositing window, and consequently the temporal reporting interval used for each period (Figures 3–8), was determined by the availability of cloud-free imagery from each Landsat series rather than by an arbitrary choice. The Landsat 5 (1993–1999) and Landsat 7 (2000–2011) archives exhibited comparatively sparser cloud-free scene availability over the HKH region, owing to persistent cloud cover of a single satellite, which necessitated coarser aggregation at annual and semi-annual intervals, respectively, to construct reliable, gap-free composites for each period. From 2013 onward, the combined Landsat 8 archive provided denser cloud-free coverage, permitting composites to be generated at a finer, quarterly interval. Consequently, snow cover trends in this study are reported at the interval best supported by data availability within each satellite era.

2.3.1. NDSI-Based Snow Cover Mapping

We processed each Landsat dataset using the Normalized Difference Snow Index (NDSI) [22,37], as shown in Equation (1). This index is a widely adopted metric for identifying and quantifying snow cover in satellite imagery. Snow has distinctive spectral properties, with high reflectance in the visible range, particularly the green band, and much lower reflectance in the shortwave infrared (SWIR) region [38]. The difference in reflectance between the visible and SWIR bands is essential for accurately detecting snow-covered areas. The NDSI technique applies a threshold to distinguish snow from non-snow surfaces, including clouds, based on their unique reflectance characteristics. Although both snow and clouds exhibit high reflectance in the visible spectrum, the key distinguishing factor lies in their behavior in the near-infrared (NIR) and SWIR regions. For Landsat 5 and Landsat 7, snow and clouds reflect strongly in band 2 (0.52–0.6 μm), whereas for Landsat 8 and Landsat 9, the green band used is band 3 (0.533–0.590 μm). However, clouds show less reduction in reflectance in the SWIR region (band 5 for Landsats 5 and 7 (1.55–1.75 μm) and band 6 for Landsats 8 and 9 (1.566–1.651 μm)) compared to snow, which allows the NDSI to filter out cloud pixels while accurately identifying snow-covered areas effectively. This filtering process enhances the precision of snow detection and minimizes misclassification errors in the satellite imagery, ensuring reliable snow cover mapping that is essential for understanding snow dynamics in the study area. We used a constant NDVI threshold (>0.4), as several researchers have used an NDSI threshold (>0.4) for snow cover mapping [37,39–43].

$$\text{NDSI} = \frac{(\text{Green} - \text{SWIR})}{(\text{Green} + \text{SWIR})} \quad (1)$$

Water Detection and Masking

The NDWI, initially proposed by [44], distinguishes water bodies from snow cover, as shown in Equation (2).

$$\text{NDWI} = \frac{(\text{Green} - \text{NIR})}{(\text{Green} + \text{NIR})} \quad (2)$$

This formula is based on the observed difference in reflectance between the green and NIR bands, a characteristic response indicative of water. The researchers used a positive NDWI threshold to delineate water bodies [45,46]. Water bodies were excluded from the final snow cover analysis to improve classification accuracy. Removing areas identified as water more accurately reflects true snow-covered surfaces and reduces potential misclassification.

2.3.2. SNOMAP Approach

The researchers [37] proposed an approach for snow detection using NDSI and NDVI. Low reflectance in the Shortwave Infrared 1 (SWIR1) band could keep the NDSI denominator low, leading to the misclassification of forested pixels as snow. To address this issue and improve snow-cover accuracy, we applied a customized approach that integrates canopy and snow reflectance models, allowing for better distinction between snow-covered and forest-covered surfaces [47]. NDVI was estimated using the formula presented in Equation (3) [48]:

$$\text{NDVI} = \frac{(\text{NIR} - \text{RED})}{(\text{NIR} + \text{RED})} \quad (3)$$

The Normalized Difference Vegetation Index (NDVI) captures the reflectance contrast between the Near-Infrared (NIR) and red bands. Areas with NDVI values equal to or above 0.08 were classified as likely forested regions, reflecting strong NIR responses

typical of dense vegetation. A binary Snow-Forest Mask (SFM) was generated by considering NDVI values below 0.12 as indicative of dense forest cover. The SFM aimed to highlight areas with characteristics of both potential snow cover and dense forests. To prevent past misclassifications, we excluded areas with green band reflectance below 10% from being classified as snow, regardless of whether they met other requirements [38].

The same SNOMAP threshold parameters were applied uniformly across all four Landsat satellites used in this study. This is justified using Landsat Collection 2, Level-2 (T1_L2) surface reflectance products for all sensors, which are generated using USGS's standardized, sensor-specific atmospheric correction algorithms to produce cross-calibrated, consistent surface reflectance for all the Landsat series. Nonetheless, differences in the relative spectral response functions between the TM/ETM+ sensors and the OLI sensor, particularly the narrower, more precisely defined near-infrared and shortwave-infrared spectral bands of the OLI sensor, may introduce small residual differences in NDVI and NDSI values not fully accounted for by Collection 2 processing alone.

2.3.3. BST Approach

A novel approach was proposed in [49], known as the Blue Snow Threshold (BST) algorithm, that leverages the blue spectral band for automated snow cover mapping. In the present study, the BST algorithm is also implemented on Landsat imagery for snow cover mapping using a maximum threshold of 0.3 in the blue band as proposed in [50].

2.3.4. Dozier and Painter Approach

The snow cover mapping method proposed in [51] utilizes reflectance values from the Near-Infrared (NIR) band in conjunction with the Normalized Difference Snow Index (NDSI). In this approach, pixels are classified as snow-covered if they meet specific threshold values for both NDSI and NIR reflectance. In this study, we refer to this method as the "Dozier approach." It has been widely adopted to produce high-resolution snow cover datasets, including those used to validate the European Space Agency's Climate Change Initiative snow products. In clear areas, a pixel is identified as snow-covered when $\text{NDSI} > 0.4$ and NIR reflectance > 0.11 , while in forest areas, a pixel is classified as snow-covered when $0.1 < \text{NDSI} < 0.4$.

Finally, we combined the snow cover maps from different approaches to estimate snow cover across several time spans. The dynamics of time series snow cover were correlated with globally available datasets of methane flux (CH_4), nitrogen flux (NO_x), carbon dioxide (CO_2), minimum temperature, maximum temperature, and precipitation. For this purpose, we created 178 random points in the snow-dominant areas of the basins of 10 large rivers in the HKH region, and used greenhouse gas, temperature, and precipitation data at these 178 points to correlate with snow cover dynamics.

2.3.5. Snow Cover Trends

To enable a single, resolution-independent measure of change across the full study period, the snow cover extent for each basin was resampled to one representative annual value for every year from 1993 to 2023, irrespective of the semi-annual or quarterly reporting interval used for display in Figures 3–8. A linear (ordinary least-squares) regression was fitted to this 30-year annual series for each basin, and the resulting slope was taken as the average annual rate of change in snow cover area (km^2/year), as reported in Figure 9. This approach isolates the long-term trend from the shorter-interval fluctuations shown in Figures 3–8 and provides a common basis for comparing rates of change across basins.

2.3.6. Point-Level Climatic Trends

For each of the 178 study points, trends in methane flux, nitrogen flux, carbon dioxide mass fraction, minimum and maximum temperatures, and precipitation were estimated as the slope of a linear (ordinary least-squares) regression fitted to that point's full monthly time series over the available record. These regression-derived rates, reported throughout Section 3.2, represent the underlying long-term trend independent of the seasonal cycle visible in the corresponding raw time-series plots (Figures 10–17), which are presented to reveal the full observed record, including seasonal variations at each point.

3. Results

3.1. Annual Snow Cover Trends

We analysed snow cover dynamics in the Hindu Kush-Himalayan (HKH) region over the past three decades, segmented into periods aligned with the operational timelines of different Landsat satellites. Leveraging data from Landsats 5, 7, 8 and the recently operational Landsat 9, this study ensures comprehensive and consistent data acquisition across the temporal span. The initial phase (1993–1999) relies on Landsat 5, capturing surface reflectance at a 30-m resolution. The subsequent phase (2000–2011) draws on Landsat 7, maintaining continuity in monitoring efforts. The final phase (2012–2023) incorporates data from Landsats 8 and 9, with enhanced spectral and spatial capabilities that refine snow cover analysis. Graphs for each phase are presented separately, corresponding to the specific durations of satellite availability, thereby clarifying the temporal variations in snow cover trends across snow- and rainfall-dominated river basins. As the reporting interval necessarily differs across these three periods, a single, resolution-independent average annual rate of change for the full 1993–2023 record is additionally presented for all ten basins in Figure 9, enabling direct comparison across basins and periods. Figure 3 presents snow cover trends from 1993 to 1999 for the basins of the major snow-dominated rivers: Amu Darya, Indus, Brahmaputra, Yangtze, and Tarim.

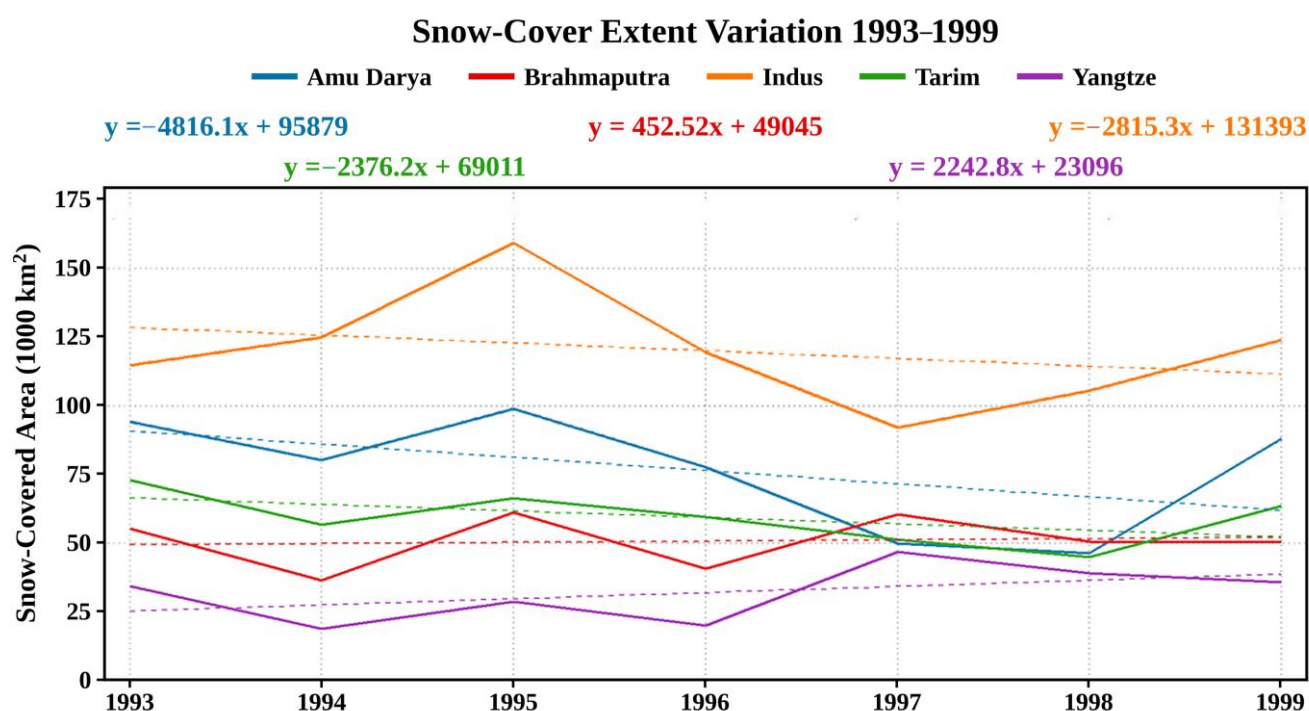


Figure 3. Snow cover extent variation of snow-dominated river basins (1993 to 1999).

The graph presents the annual snow cover extent variation of snow-dominated river basins (Amu Darya, Indus, Brahmaputra, Yangtze, Tarim) of the HKH region from 1993 to 1999. Notably, the Amu Darya basin showed a consistent decline, with snow cover decreasing by approximately 4816.1 km²/year. The Brahmaputra River basin showed a steady increase, with an average annual gain of approximately 452.5 km² per year. In contrast, the Indus River basin exhibited a consistent decline, losing around 2815.3 km² annually. The Tarim River Basin also showed a downward trend, with snow cover decreasing by about 2376.2 km² per year. Meanwhile, the Yangtze River basin showed more variability but overall indicated an increasing trend, with an average rise of roughly 2242.8 km² annually.

Figure 4 presents snow cover trends from 1993 to 1999 for the minor rainfall-dominated river basins of the Ganges, Irrawaddy, Mekong, Salween, and Yellow.

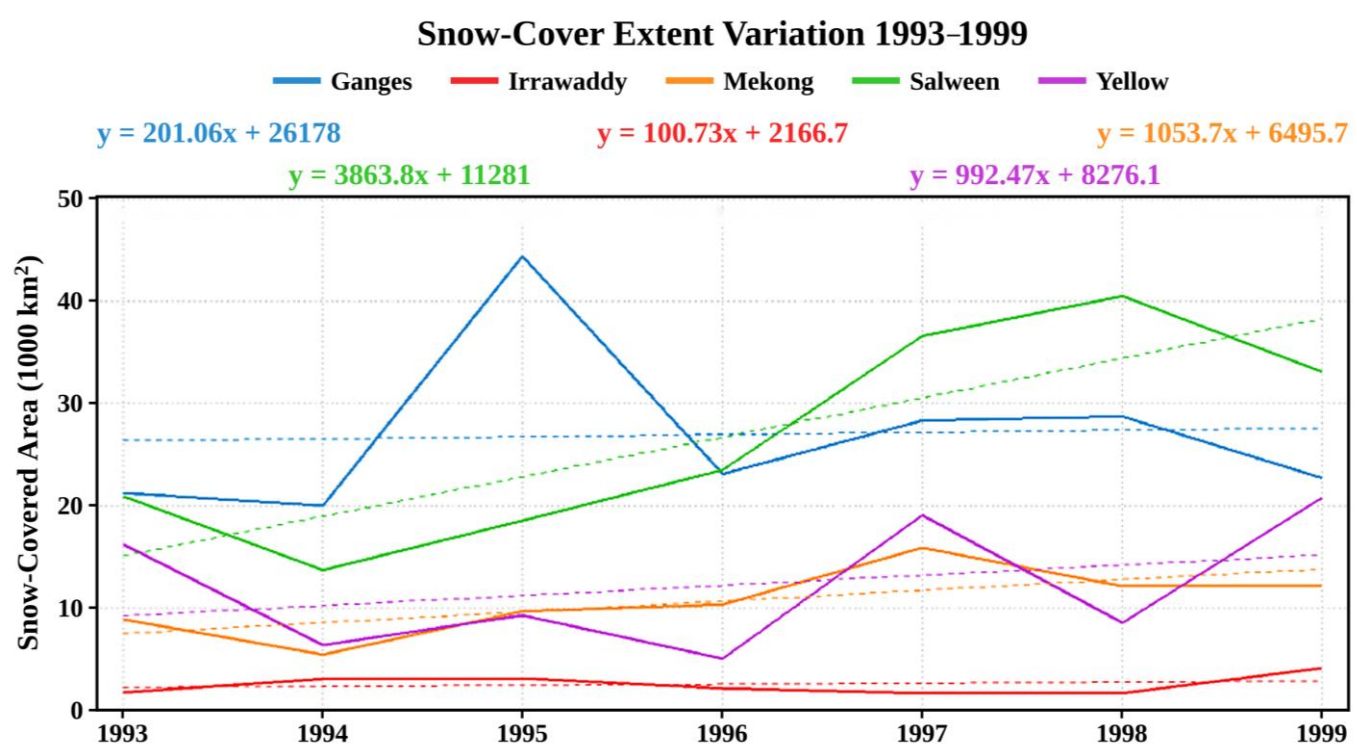


Figure 4. Snow cover extent variation of rainfall-dominated river basins (1993 to 1999).

The graph illustrates annual snow cover variations in the rainfall-dominated river basins from 1993 to 1999. The Ganges River basin showed a fluctuating pattern, with an average annual increase of about 201.1 km². Similarly, the Irrawaddy and Mekong river basins showed variable trends, with average increases of about 100.7 km² and 1053.7 km² per year, respectively. The Salween River basin showed the highest increase, averaging around 3863.8 km² annually. The Yellow River basin also displayed a fluctuating trend, with snow cover expanding by roughly 992.5 km² per year.

Figure 5 presents snow cover trends from 2000 to 2011 for the snow-dominated major river basins: Amu Darya, Indus, Brahmaputra, Yangtze, and Tarim. The graph shows variations in snow cover extent from October 1999 to September 2011. The Amu Darya basin exhibited a steady decline, with snow cover decreasing at an average rate of approximately 1465.8 km² every six months.

In contrast, the Brahmaputra River basin showed an upward trend, with snow cover increasing by an average of 75.2 km² every six months. The Indus River Basin continued its decline, losing about 1331.5 km² over the same period. Similarly, the Tarim River Basin decreased steadily by about 558.6 km², while the Yangtze River Basin also declined, with

an average reduction of 523.5 km² every six months. These findings highlight the diverse snow cover dynamics across the snow-dominated river basins between October 1999 and September 2011.

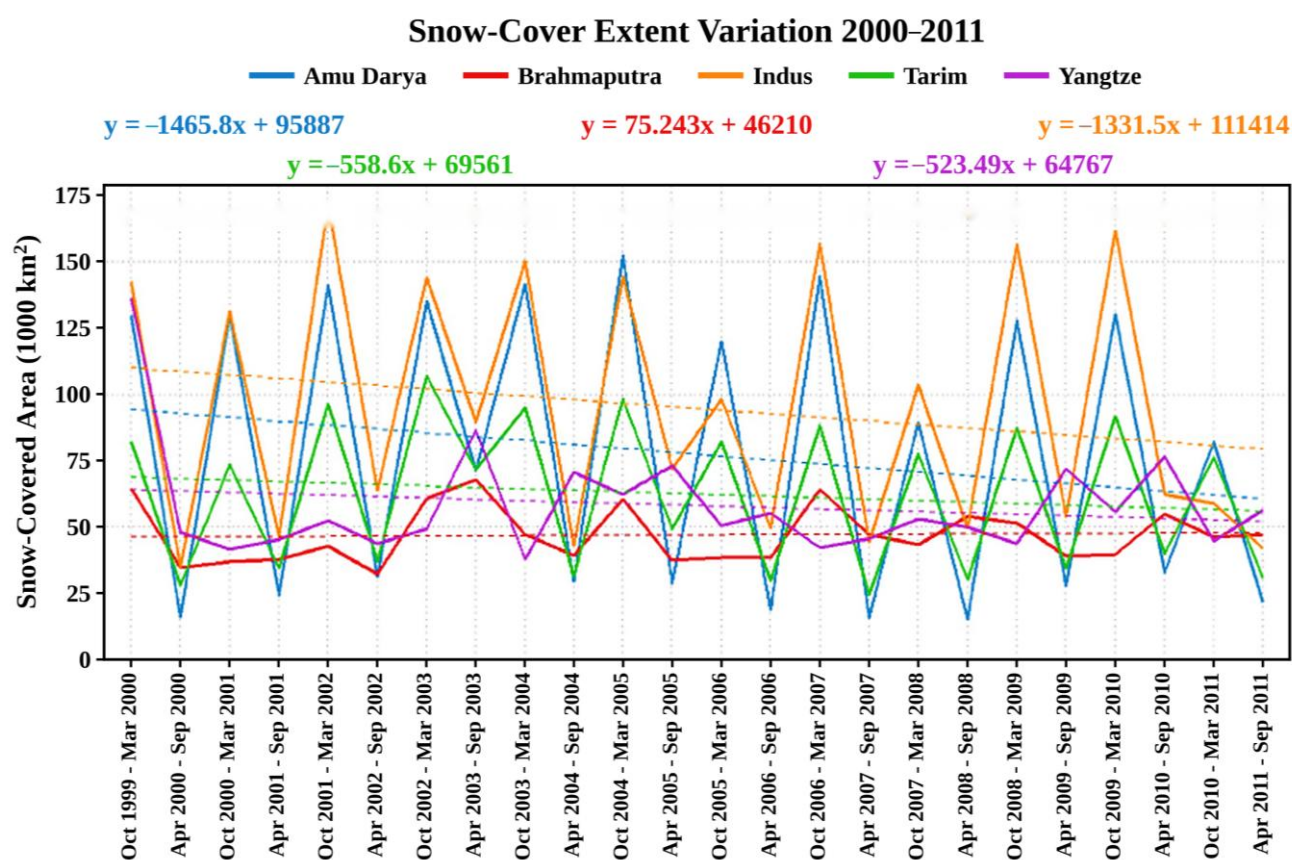


Figure 5. Snow cover extent variation of snow-dominated river basins (October 1999 to September 2011).

Figure 6 presents snow cover trends from 2000 to 2011 for the rainfall-dominated minor river basins: Ganges, Irrawaddy, Mekong, Salween, and Yellow. The graph illustrates changes in snow cover extent from October 1999 to September 2011. The Ganges River basin showed a declining trend, with an average reduction of about 236.6 km² every six months. In contrast, the Irrawaddy River basin experienced an increase of approximately 244.8 km² over the same period. The Mekong River Basin also showed a decreasing pattern, with snow cover declining by around 107.7 km² every six months.

In contrast, the Salween River basin showed an increasing trend, with snow cover expanding by approximately 76.2 km² every six months. Meanwhile, the Yellow River Basin (YRB) experienced a decline, with an average reduction of around 326.6 km² over the same period. These findings highlight the varied patterns of snow cover dynamics across the rainfall-dominated river basins from October 1999 to September 2011.

Figure 7 presents snow cover trends from 2012 to 2023 for the snow-dominated basins: Amu Darya, Indus, Brahmaputra, Yangtze, and Tarim. The graph shows snow cover extent variations from January 2012 to December 2023, based on quarterly data. During this period, the Amu Darya basin showed a consistent decline, with snow cover decreasing by about 310.5 km² each quarter. The Brahmaputra and Indus river basins also showed downward trends, with average reductions of about 209.5 km² and 241.7 km², respectively, per quarter. In comparison, the Tarim River basin experienced a relatively small decline of around 7.4 km² every three months.

Lastly, the Yangtze River basin demonstrated a significant decline, with snow cover decreasing by approximately 815.01 km² every three months.

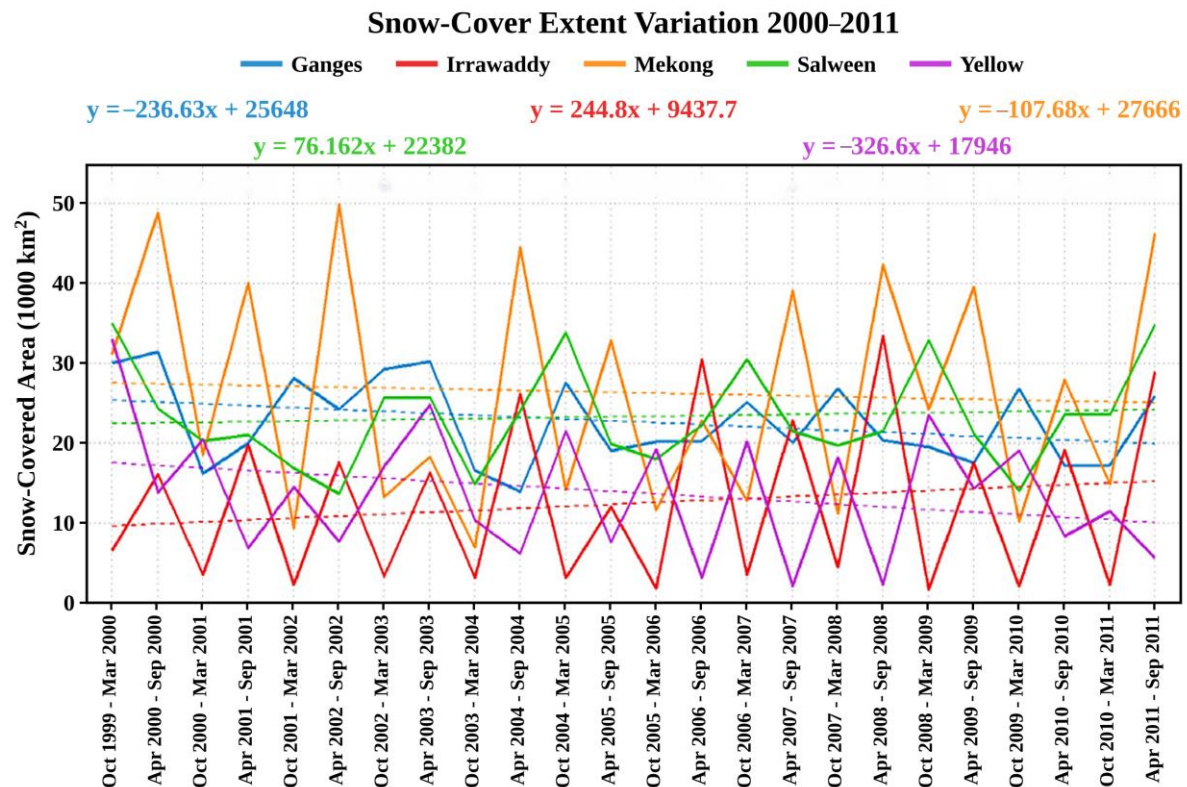


Figure 6. Snow cover extent variation of rainfall-dominated river basins (October 1999 to September 2011).

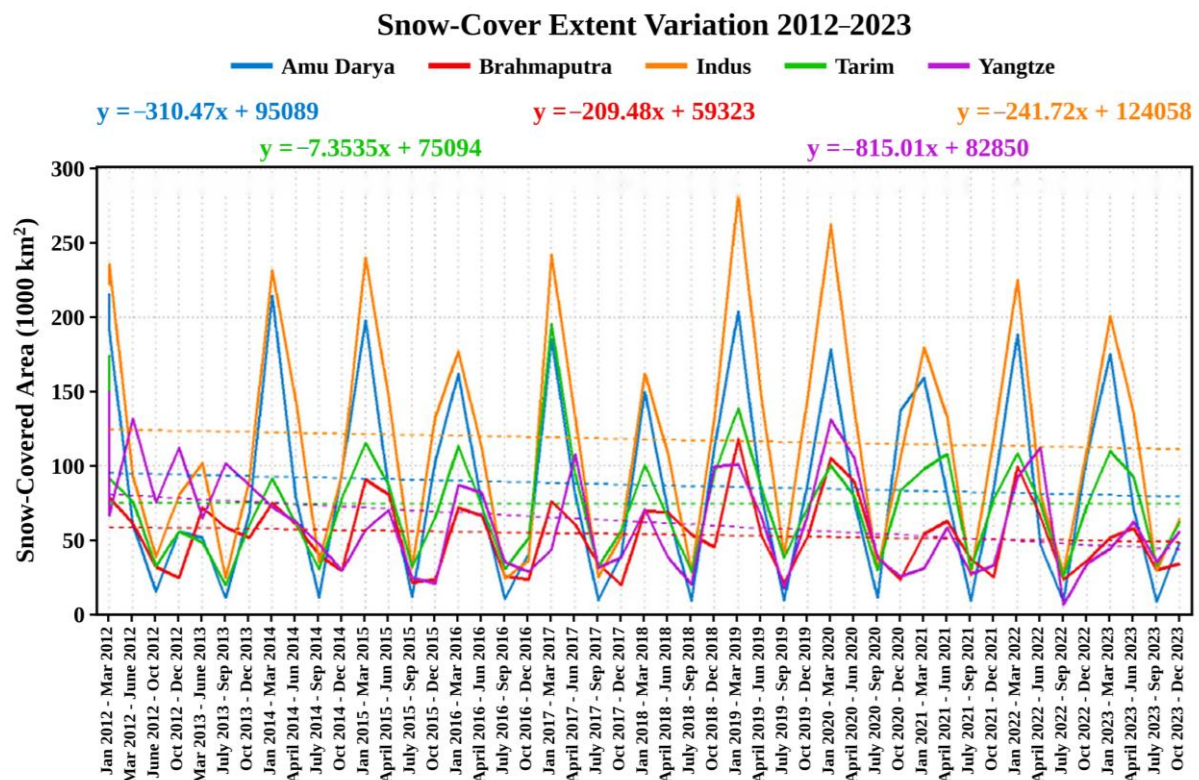


Figure 7. Snow cover extent variation of snow-dominated river basins (January 2012 to December 2023).

Figure 8 presents snow cover trends from 2012 to 2023 for the rainfall-dominated minor river basins: Ganges, Irrawaddy, Mekong, Salween, and Yellow. The graph illustrates quarterly changes in snow cover extent from January 2012 to December 2023. The Ganges River Basin showed a declining trend, with snow cover decreasing by about 55.0 km² every three months. Similarly, the Irrawaddy and Mekong river basins declined, with average reductions of about 124.1 km² and 254.5 km², respectively. In contrast, the Salween River basin exhibited a slight increase of around 25.1 km² per quarter, while the Yellow River basin showed a more notable rise, averaging 110.5 km² every three months.

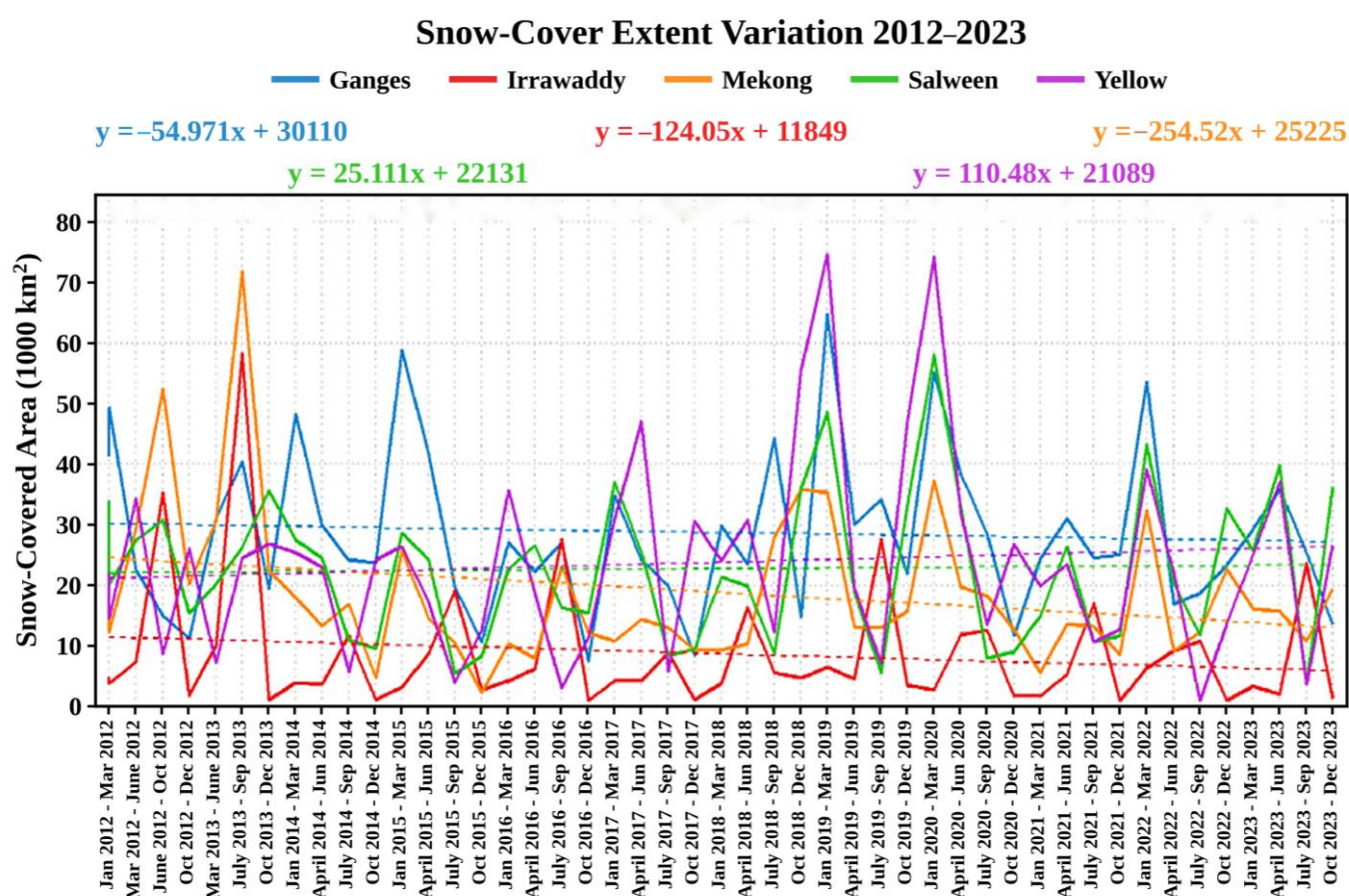


Figure 8. Snow cover extent variation of rainfall-dominated river basins (January 2012 to December 2023).

The graph (Figure 9) highlights both increasing and decreasing trends in snow cover area, represented by green and red bars, respectively. Among all river basins, the Amu Darya exhibited the most significant decline, with an average annual reduction of approximately 2793.15 km². This was followed by the Indus River basin, which showed a substantial decrease of 2108.86 km² per year. The Tarim River basin also recorded a considerable decline, averaging 1013.09 km² annually. Similarly, the Yangtze and Ganges river basins experienced notable reductions in snow cover, with average annual losses of 1199.49 km² and 230.34 km², respectively. The Mekong and Brahmaputra river basins showed moderate decreases, averaging 247.51 km² and 169.39 km² per year. In contrast, the Salween River basin displayed a significant increase in snow cover, with an annual gain of approximately 1002.66 km². The Yellow and Irrawaddy river basins also exhibited minor increases, with annual growth rates of 147.06 km² and 20.86 km², respectively. Overall, the graph shows a predominant trend of diminishing snow cover across most river basins, reflecting the broader impacts of climate change in the Hindu Kush-

Himalayan (HKH) region. The pronounced declines in the Amu Darya, Indus, Tarim, Yangtze, Ganges, Mekong, and Brahmaputra river basins are especially concerning, as reduced snow cover in these areas may significantly affect downstream water availability, hydrological regimes, and ecological stability.

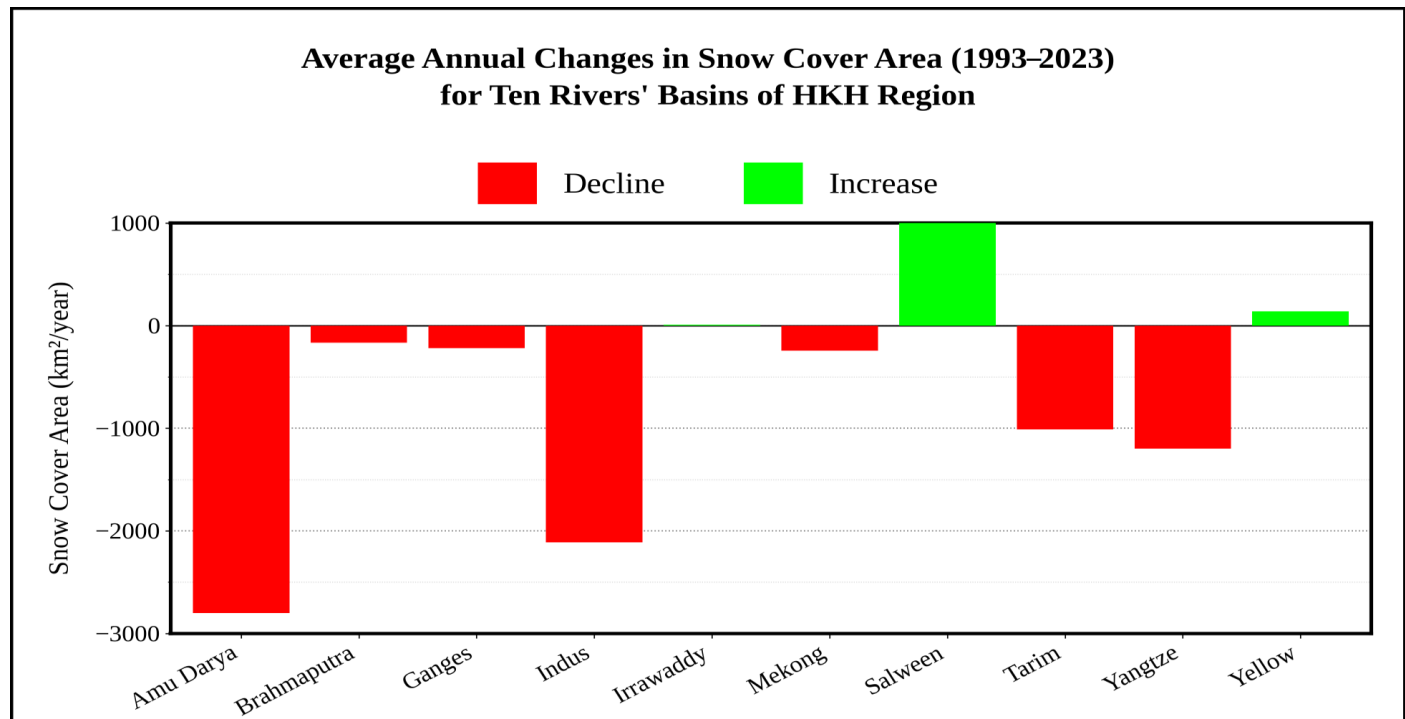


Figure 9. Average annual change in snow cover area (1993–2023) for the ten HKH river basins, calculated as the linear trend of each basin’s annually resampled snow cover run. Green bars: increasing trend; red bars: decreasing trend.

3.2. Relationship Between Snow Cover Dynamics and Climatic Variables

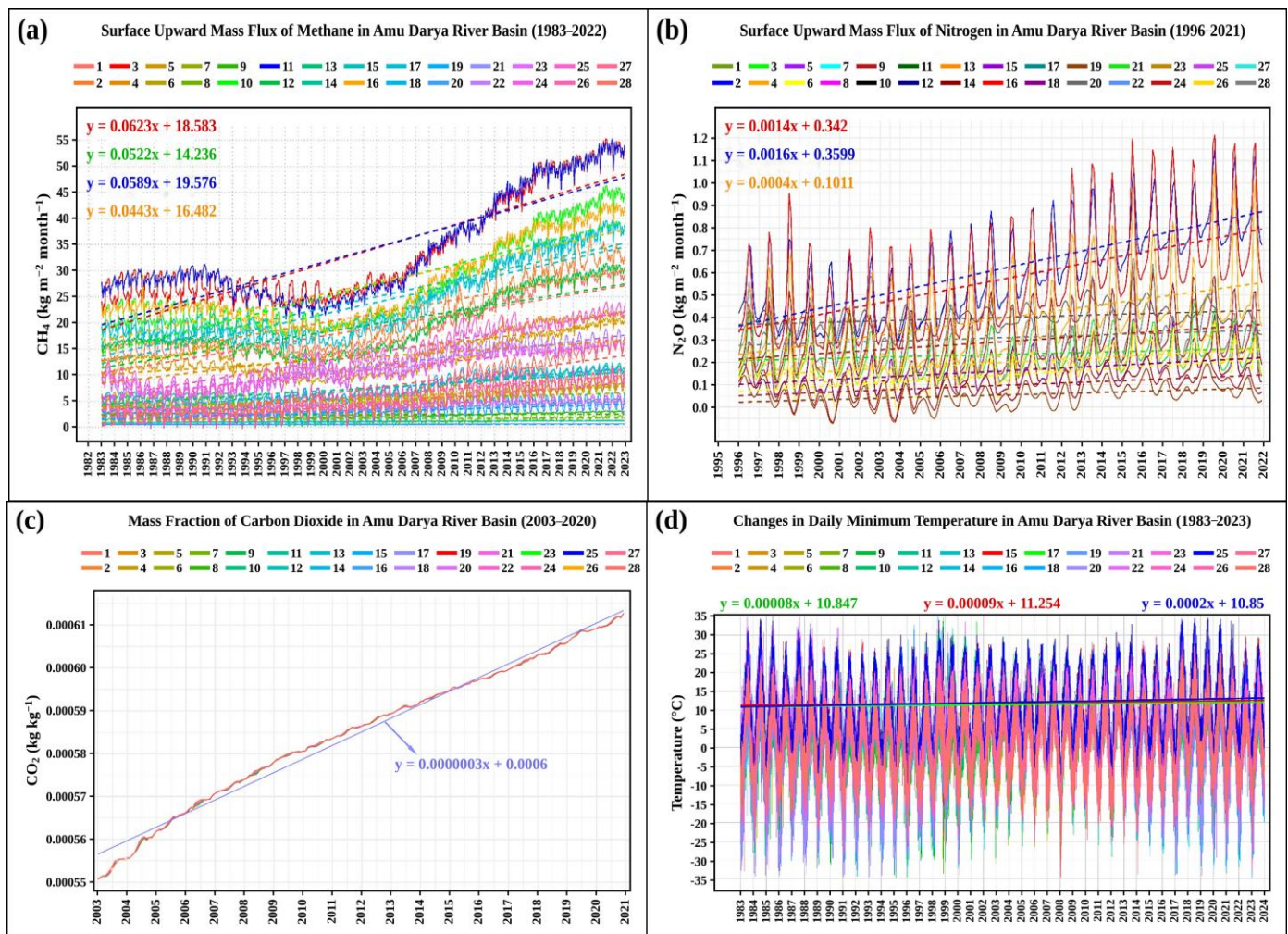
The rates of change of climatic variables for each point were derived from linear regression on the full monthly time series and therefore reflect the trend independent of the seasonal cycle visible in Figures 10–17, which show the complete observational record at each point.

3.2.1. Amu Darya Basin

Over the past thirty years, the Amu Darya basin has experienced a marked and progressively intensifying decline in snow cover. From 1993 to 2023, the snow-covered area decreased by an average of about 2793.15 km² per year. This trend unfolded in distinct stages. The most rapid reduction occurred during 1993–1999, with annual losses averaging about 4816.1 km². Between 2000 and 2011, the decline continued at a faster pace, with losses of about 1465.8 km² recorded every six months. The downward trend intensified from 2012 to 2023, when snow cover decreased by roughly 310.47 km² each quarter. This steady loss appears linked to climatic shifts, such as increased atmospheric greenhouse gas concentrations, rising temperatures, and evolving precipitation regimes. Investigating these contributing factors offers valuable insight into changes in the region’s snow cover.

Figure 10a,b illustrates the temporal evolution of methane and nitrogen fluxes within the Amu Darya basin, indicating a pronounced upward trend. At Point 3, methane emissions have risen by approximately 0.0623 kg/m² per month, while Point 11 has recorded a comparable increase of about 0.0589 kg/m² per month. Similarly, nitrogen

fluxes have also risen, with Point 2 recording a monthly increase of 0.0016 kg/m² and Point 16 showing a rise of 0.0014 kg/m² from 1996 to 2021. These increases in greenhouse gas emissions significantly contribute to regional warming trends that affect snowmelt processes, thereby intensifying snow cover loss. The CO₂ data in Figure 10c show a steady rise in the mass fraction of carbon dioxide between 2003 and 2020. Across the 28 selected points in the river basin, the monthly increase in CO₂ mass fraction was 0.0000003 kg/kg. Although subtle, this increase contributes cumulatively to the overall rise in atmospheric CO₂ concentrations, a major driver of the greenhouse effect and regional warming. This in turn accelerates snowmelt and reduces snow cover within the river basin. Figure 10d and e illustrates notable increases in both daily minimum and maximum temperatures, which further contribute to snow cover reduction. The maximum daily temperature at Points 9 and 10 has risen by 0.0001 °C/day and 0.0004 °C/day, respectively, between 1983 and 2023. Meanwhile, the minimum daily temperatures at Points 25 and 15 have increased by 0.0002 °C/day and 0.00009 °C/day, respectively. The gradual warming observed in the river basin contributes directly to snowmelt processes, resulting in less snow accumulation and faster melting during the winter months. Precipitation variability, shown in Figure 10f, compounds the effects of rising temperatures. Monthly precipitation has declined at several points in the river basin, with Point 7 recording a reduction of 0.0109 mm/month, Point 5 recording a decrease of 0.0174 mm/month and Point 11 recording a decline of 0.054 mm/month from 1990 to 2019. This reduction in precipitation, combined with rising temperatures and greenhouse gas concentrations, has contributed to less snowfall, diminished snowpack, and increased rates of snowmelt.



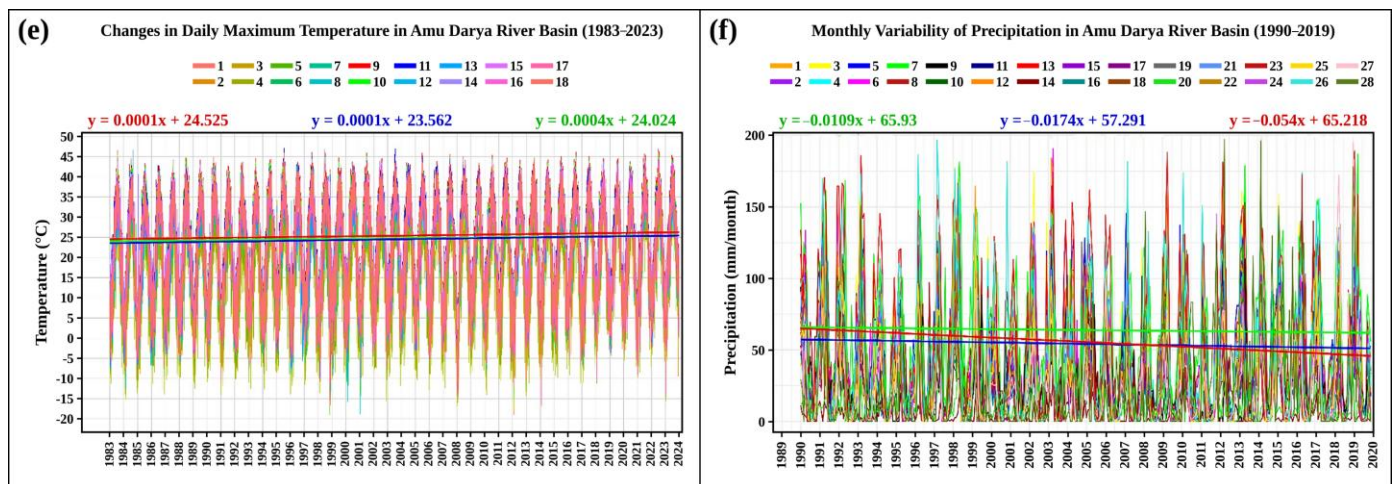


Figure 10. (a–f) Temporal trends of key climatic and environmental variables in the Amu Darya basin: (a) methane flux (CH_4), (b) nitrogen flux (NO_x), (c) carbon dioxide (CO_2) mass fraction, (d) minimum temperature changes, (e) maximum temperature changes, (f) monthly precipitation variability. Point numbers refer to the basin-localized subset of the 178 study points described in Section 2.1 and Figure 2.

3.2.2. Indus River Basin (IRB)

The Indus River Basin has undergone a marked decline in snow cover over the past three decades, with an average annual reduction of approximately 2108.86 km^2 between 1993 and 2023. This downward trend unfolded over three distinct periods. From 1993 to 1999, snow cover diminished steadily, averaging around 2815.3 km^2 per year. From 2000 to 2011, the loss accelerated, with snow cover decreasing by about 1331.5 km^2 every six months. More recently, between 2012 and 2023, the decline continued at an average rate of 241.72 km^2 every three months. This persistent reduction is closely linked to climate shifts, particularly rising levels of greenhouse gases such as methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) within the river basin. Figure 11a,b shows a clear upward trend in methane and nitrogen emissions, both of which serve as important indicators of environmental change. At Point 11, methane flux has increased by approximately 0.2174 kg/m^2 per month, while Point 16 exhibits a similar monthly increase of 0.2106 kg/m^2 . Nitrogen fluxes have also risen, with Point 18 showing a monthly increase of 0.0039 kg/m^2 and Point 24 increasing by 0.0032 kg/m^2 . These patterns suggest a growing presence of greenhouse gases, likely driven by human activities in the region. Furthermore, Figure 11c displays a consistent rise in CO_2 mass fraction across 28 monitoring points within the river basin, with an observed monthly increase of 0.0000003 kg/kg from 2003 to 2020.

While the increment appears minor, its long-term accumulation contributes meaningfully to warming trends, accelerating snow and ice melting in the region. Together, these findings emphasize the strong influence of atmospheric changes on snow cover dynamics in the Indus River Basin. Temperature fluctuations are crucial to understanding snow cover dynamics in the Indus River Basin. Figure 11d,e depicts the gradual increase in maximum and minimum temperatures. Specifically, Points 11 and 17 exhibited rising maximum daily temperatures at rates of 0.0003 $^\circ\text{C}/\text{day}$ and 0.0001 $^\circ\text{C}/\text{day}$, respectively, while minimum daily temperatures at Points 11 and 25 increased at rates of 0.0001 $^\circ\text{C}/\text{day}$ and 0.00008 $^\circ\text{C}/\text{day}$, respectively. These temperature changes are key drivers of snowmelt and significantly affect water resources in the river basin. Variability in precipitation, shown in Figure 11f, reveals a decreasing trend across various points, particularly at Point 3, which shows a decline of 0.0599 mm/month , point 20, which shows a reduction of 0.0529 mm/month , and Point 11, where precipitation levels dropped by

0.0047 mm/month. Decreasing precipitation, along with rising greenhouse gas emissions and temperature increases, highlights the complex interactions among these factors and their contributions to snow cover dynamics and water resource availability in the Indus River Basin.

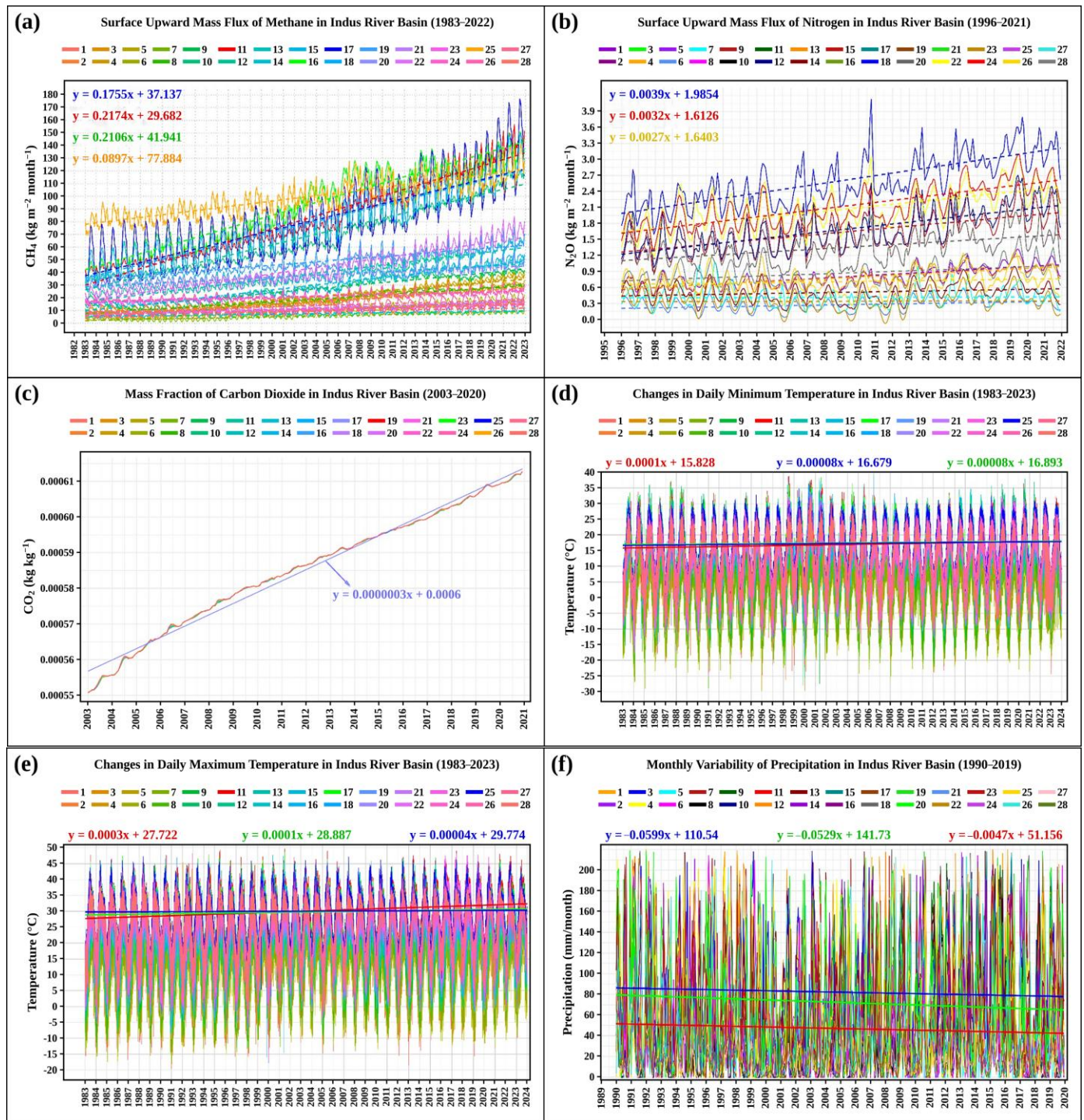


Figure 11. (a–f) Temporal trends of key climatic and environmental variables in the Indus River Basin: (a) methane flux (CH_4), (b) nitrogen flux (NO_x), (c) carbon dioxide (CO_2) mass fraction, (d) minimum temperature changes, (e) maximum temperature changes, (f) monthly precipitation variability. Point numbers refer to the basin-localized subset of the 178 study points described in Section 2.1 and Figure 2.

3.2.3. Yangtze River Basin (YRB)

The Yangtze River Basin has experienced a fluctuating and ultimately declining trend in snow cover over the past three decades, with an average annual decrease of 1199.49 km² from 1993 to 2023. This trend occurred in three distinct phases. From 1993 to 1999, the river basin experienced an initial increase in snow cover, with an average gain of 2242.8 km² per year. However, this upward trend reversed sharply between 2000 and 2011, when snow cover declined by about 523.49 km² every six months. The reduction became more pronounced from 2012 to 2023, with snow cover decreasing at a rate of 815.01 km² every three months. This substantial loss is closely associated with climatic drivers such as temperature variations and rising greenhouse gas emissions. Increased concentrations of methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O) in the Yangtze River Basin have contributed to global warming. These changes accelerate snowmelt processes and disrupt natural snow accumulation patterns. Understanding snow cover dynamics is essential to evaluating the region's long-term hydrological and environmental consequences. The ongoing decline in snow reserves highlights the need for sustained monitoring and adaptive water management strategies to protect downstream ecosystems and ensure water security.

In Figure 12a, trend lines for methane concentrations at Points 7 and 13 show a consistent increase in surface-level emissions over time. Point 7 records a monthly rise of 0.0223 kg/m² in methane flux, while Point 13 shows a smaller but notable increase of 0.0035 kg/m². These trends reflect a steady buildup of methane in localized areas. Figure 12b shows nitrogen flux trends, with Point 24 increasing by 0.0016 kg/m² per month and Point 22 by 0.001 kg/m². These patterns suggest that anthropogenic emissions significantly influence atmospheric composition in the Yangtze River Basin. Additionally, the mass fraction of carbon dioxide (CO₂), as shown in Figure 12c, shows a steady upward trend across 28 selected locations in the river basin from 2003 to 2020.

The monthly increase of 0.0000003 kg/kg, though small, has a cumulative impact that contributes meaningfully to rising atmospheric CO₂ levels and climate variability in the region. Temperature trends are another critical factor influencing snow cover dynamics. Figure 12d,e depicts increasing daily maximum and minimum temperatures at several points in the river basin. At Points 13 and 15, maximum temperatures are rising at a rate of 0.0002 °C per day. Similarly, minimum temperatures are increasing at Points 13 and 24, with rates of 0.0002 °C/day and 0.0001 °C/day, respectively. These gradual increases intensify snowmelt and compromise snowpack stability, directly affecting water availability and seasonal runoff patterns. Finally, the trends in precipitation variability, as shown in Figure 12f, show declines at multiple points. Notably, point 23 decreased by 0.0249 mm/month, Point 20 decreased by 0.0153 mm/month, and Point 21 decreased by 0.0119 mm/month from 1990 to 2019. Declining precipitation trends, coupled with rising greenhouse gas emissions and increasing temperatures, highlight the complex interactions driving hydrometeorological dynamics and altering snow cover patterns in the Yangtze River Basin.

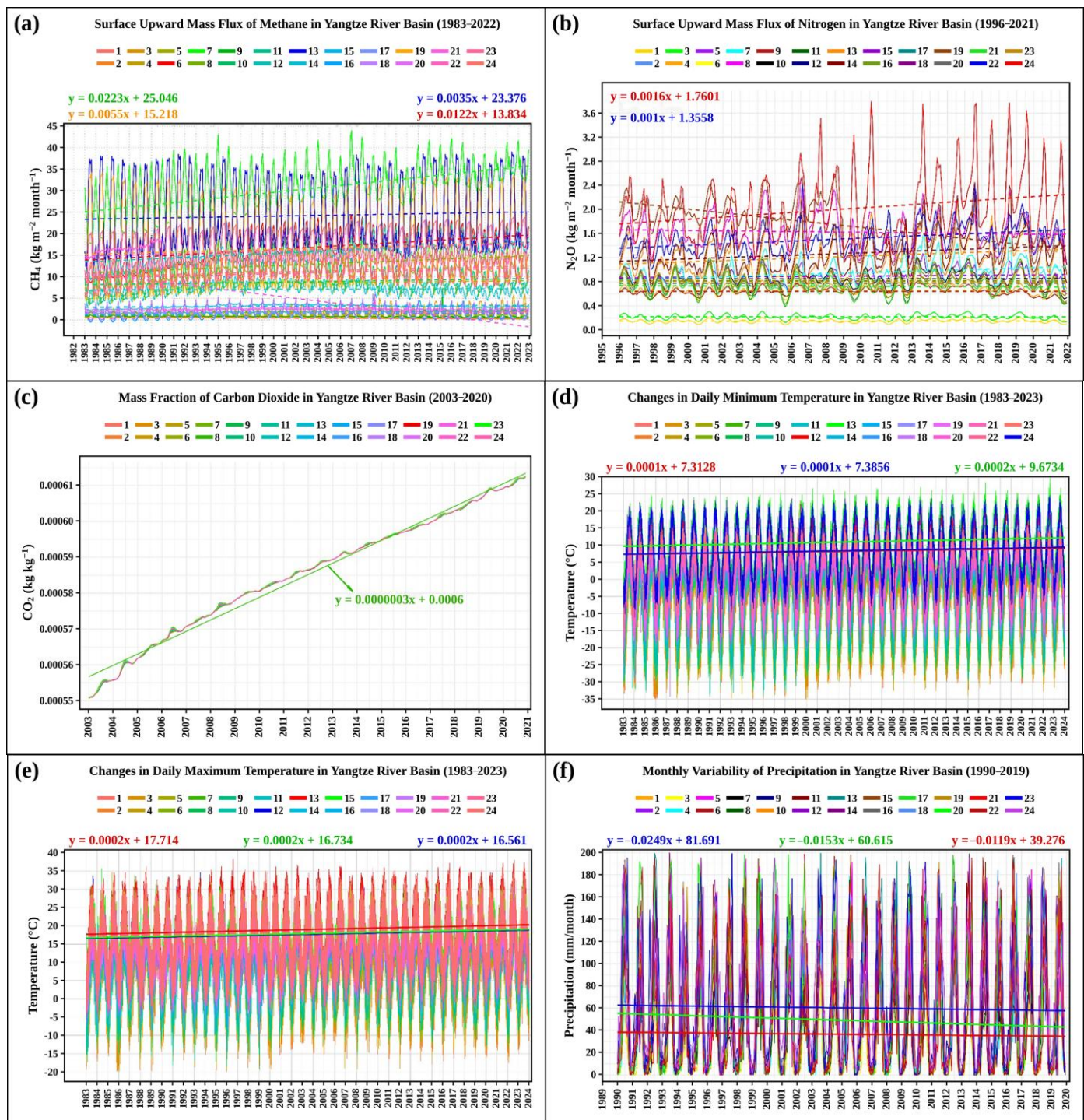


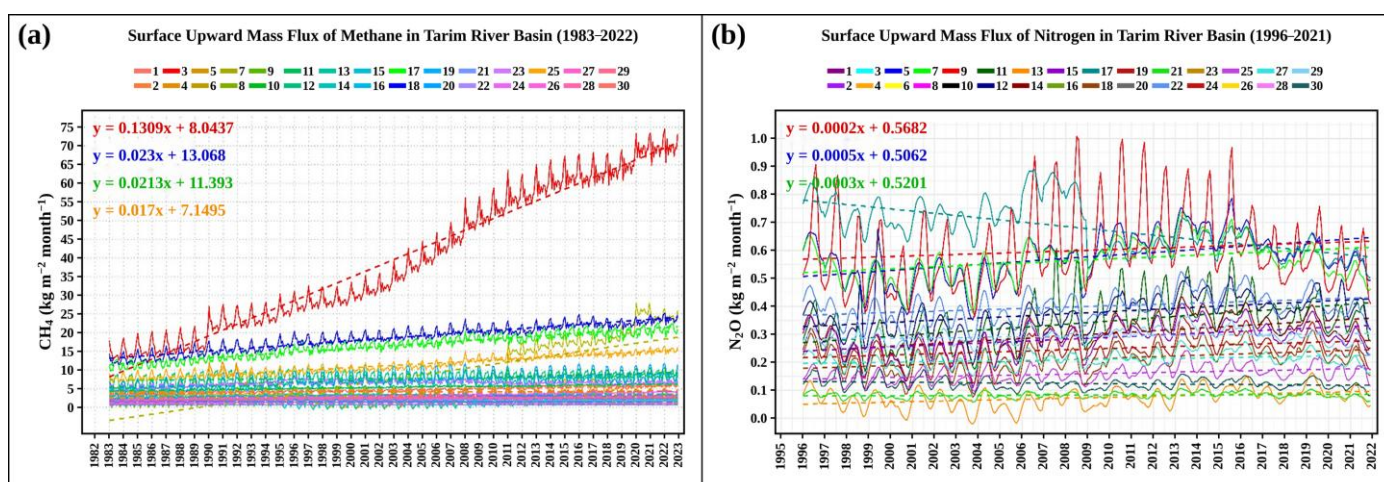
Figure 12. (a–f) Temporal trends of key climatic and environmental variables in the Yangtze River Basin: (a) methane flux (CH_4), (b) nitrogen flux (NO_x), (c) carbon dioxide (CO_2) mass fraction, (d) minimum temperature changes, (e) maximum temperature changes, (f) monthly precipitation variability. Point numbers refer to the basin-localized subset of the 178 study points described in Section 2.1 and Figure 2.

3.2.4. Tarim River Basin (TRB)

From 1993 to 2023, the Tarim River Basin experienced a considerable reduction in snow cover, averaging an annual loss of approximately 1013.09 km^2 . This decline occurred in three distinct phases. During the first phase, from 1993 to 1999, the region saw a sharp decrease in snow cover, with an average annual loss of around 2376.2 km^2 . The second phase, from 2000 to 2011, continued the downward trend, with a reduction of about 558.6

km² every six months. In the third phase, spanning 2012 to 2023, the rate of decline slowed significantly, averaging a loss of just 7.35 km² every three months. This ongoing reduction in snow cover is strongly associated with rising levels of greenhouse gases such as methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O). These gases contribute to global temperature increases, which accelerate snowmelt and alter snowfall patterns. Diminishing snow reserves have serious implications for regional water resources, particularly in arid environments like the Tarim River Basin. To address these challenges, continuous monitoring and the adoption of adaptive water management strategies are critical.

As shown in Figure 13a, the methane concentration trend lines for Points 3 and 18 show a consistent monthly increase in surface upward mass flux, with Point 3 rising by 0.1309 kg/m² and Point 18 rising by 0.023 kg/m². Similarly, nitrogen emissions show an upward trend. Figure 13b illustrates increasing nitrogen flux trends, with Point 5 showing a monthly increase of 0.0005 kg/m² and Point 7 showing a rise of 0.0003 kg/m². These emissions contribute significantly to the region's changing environmental conditions. The mass fraction of carbon dioxide (CO₂) across 28 selected points in the Tarim River Basin, as depicted in Figure 13c, has increased steadily from 2003 to 2020, with a monthly rise of 0.0000003 kg/kg. This gradual increase in CO₂ concentration is consistent with broader trends of rising anthropogenic emissions. Temperature trends also play a pivotal role in changing snow dynamics in the Tarim River Basin. Figure 13d highlights rising maximum daily temperatures, with Points 18 and 21 showing increases of 0.0002 °C/day and 0.0001 °C/day, respectively. In contrast, minimum temperatures, shown in Figure 13e, also show upward trends, with Point 18 increasing by 0.0003 °C/day and Point 25 increasing by 0.0002 °C/day. Temperature fluctuations play a vital role in snowmelt rates and the overall stability of snow cover in the Tarim River Basin. In addition to warming trends, precipitation patterns have also shifted over time. As illustrated in Figure 13f, several locations within the river basin show a clear downward trend in monthly precipitation between 1990 and 2019. Specifically, point 14 recorded a decline of 0.0109 mm per month, point 16 saw a decrease of 0.0104 mm per month and Point 13 experienced a smaller reduction of 0.0016 mm per month. Alongside the consistent rise in temperature and increased greenhouse gas concentrations, these precipitation declines highlight the intricate, interrelated climate dynamics reshaping the region's snow cover and water systems.



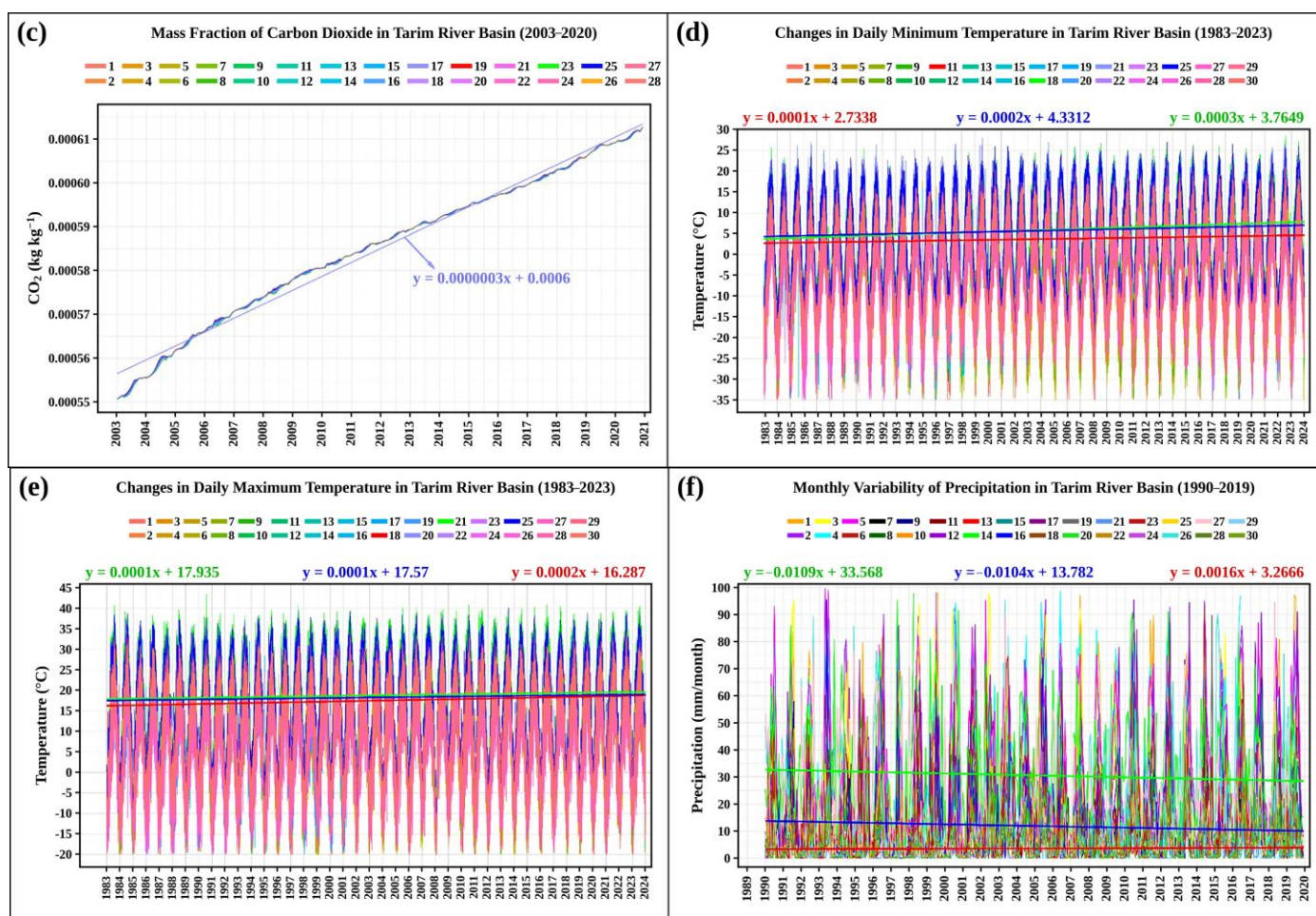


Figure 13. (a–f). Temporal trends of key climatic and environmental variables in the Tarim River Basin: (a) methane flux (CH_4), (b) nitrogen flux (NO_x), (c) carbon dioxide (CO_2) mass fraction, (d) minimum temperature changes, (e) maximum temperature changes, (f) monthly precipitation variability. Point numbers refer to the basin-localized subset of the 178 study points described in Section 2.1 and Figure 2.

3.2.5. Brahmaputra River Basin (BRB)

The Brahmaputra River Basin has shown variable snow cover dynamics over the past three decades. Between 1993 and 1999, snow-covered areas expanded at an average rate of 452.52 km^2 per year. This upward trend continued from 2000 to 2011, though more slowly, with an average increase of 75.24 km^2 every six months. In contrast, from 2012 to 2023, the river basin saw a sharp reduction in snow cover, averaging 209.48 km^2 every three months. This recent decline is closely linked to rising concentrations of greenhouse gases, including methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), which intensify the greenhouse effect. As global temperatures rise, the rate of snowmelt accelerates, and seasonal snow accumulation becomes increasingly erratic. Trends in greenhouse gas emissions across the river basin reinforce this link. Figure 14a highlights the steady increase in methane concentrations at Points 11 and 13. At Point 11, methane flux rose by 0.0023 kg/m^2 per month, while Point 13 recorded a slightly higher increase of 0.0039 kg/m^2 per month. Figure 14b illustrates similar upward trends in nitrogen emissions.

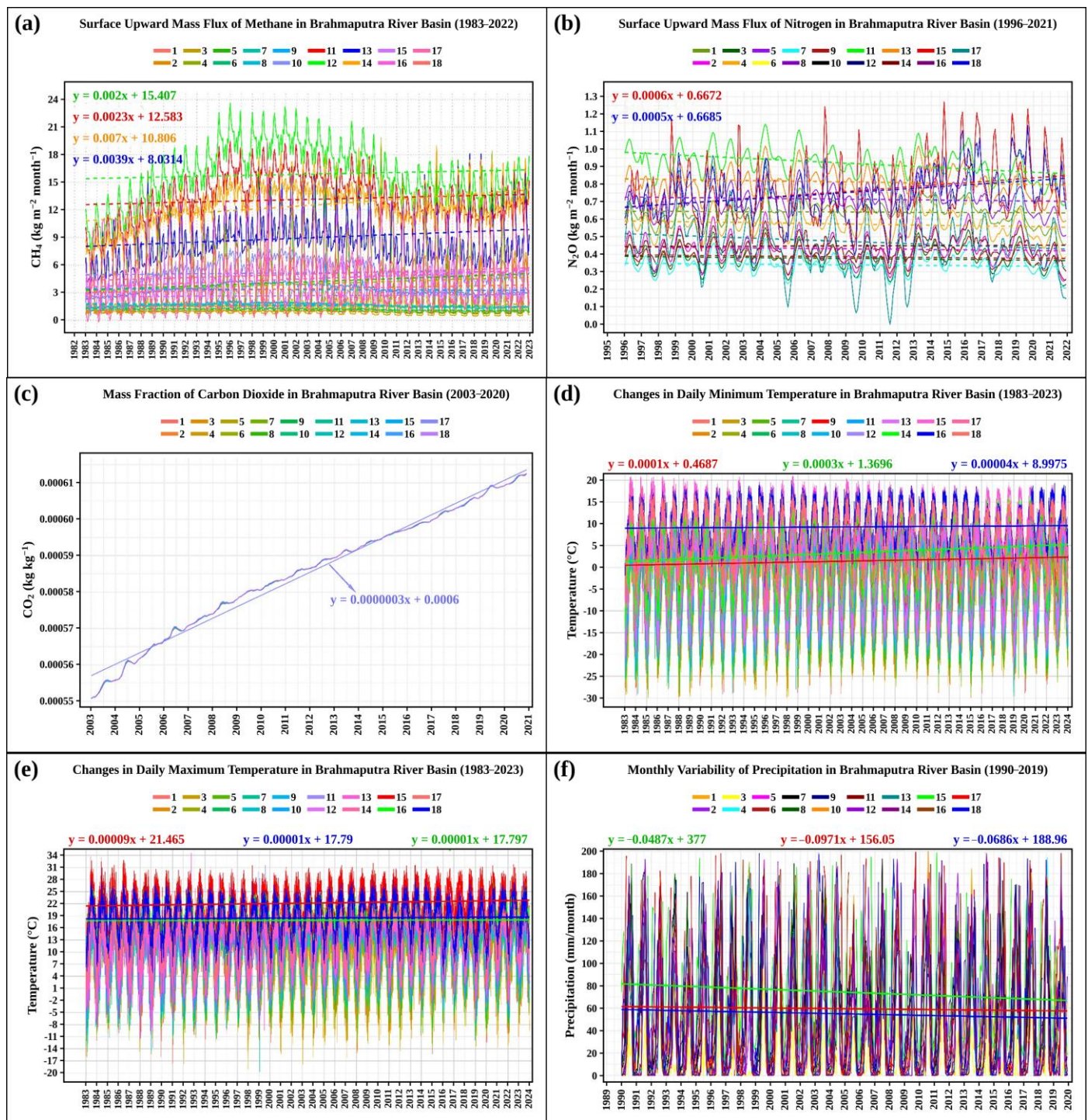


Figure 14. (a–f) Temporal trends of key climatic and environmental variables in the Brahmaputra River Basin: (a) methane flux (CH_4), (b) nitrogen flux (NO_x), (c) carbon dioxide (CO_2) mass fraction, (d) minimum temperature changes, (e) maximum temperature changes (f) monthly precipitation variability. Point numbers refer to the basin-localized subset of the 178 study points described in Section 2.1 and Figure 2.

Figure 14c shows that the mass fraction of CO_2 across 28 selected points in the Brahmaputra river basin steadily rose from 2003 to 2020. The monthly rise in CO_2 mass fraction is 0.0000003 kg/kg , reflecting broader trends of increasing anthropogenic CO_2 emissions. Temperature trends are also crucial in understanding snow dynamics in the Brahmaputra River basin. As depicted in Figure 14d, maximum daily temperatures have been increasing, with Point 15 showing a gradual rise of $0.00009 \text{ }^\circ\text{C/day}$ and Point 18

showing an increase of $0.00001\text{ }^{\circ}\text{C/day}$ from 1983 to 2023. Minimum temperatures have also risen, as shown in Figure 14e, with Point 9 and Point 14 experiencing increases of $0.0001\text{ }^{\circ}\text{C/day}$ and $0.0003\text{ }^{\circ}\text{C/day}$, respectively. These temperature changes play a significant role in the observed snow dynamics. Precipitation trends, illustrated in Figure 14f, reveal a notable decrease across the river basin. From 1990 to 2019, Point 15 saw a reduction of 0.0487 mm/month , point 17 decreased by 0.0971 mm/month , and Point 18 decreased by 0.0686 mm/month . This decrease in precipitation, coupled with rising temperatures and greenhouse gas concentrations, highlights the complex interplay of factors affecting snow cover and hydrology in the Brahmaputra River basin.

3.2.6. Ganges River Basin (GRB)

The Ganges River Basin has undergone a significant reduction in snow cover over the past three decades, with an average annual loss of about 230.34 km^2 from 1993 to 2023. This downward trend has not been uniform throughout the period. From 1993 to 1999, the region experienced a moderate annual increase in snow cover, averaging around 201.06 km^2 . However, the pattern reversed between 2000 and 2011, with snow cover declining at an average rate of 236.63 km^2 every six months. The decline continued from 2012 to 2023, though more slowly, with a reduction of about 54.97 km^2 every three months. The ongoing loss of snow cover is closely linked to increased atmospheric concentrations of greenhouse gases, including methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). These gases intensify the greenhouse effect by trapping heat, raising temperatures across the region. The resulting warming accelerates snowmelt and disrupts normal snowfall and melt cycles, contributing to the persistent decline in snow cover observed in the Ganges River basin in recent decades.

Figure 15a shows the trend lines for methane concentrations at Points 4 and 5. Point 4 exhibits a consistent monthly increase in methane mass flux of 0.0373 kg/m^2 , while Point 5 shows a slightly lower increase of 0.0225 kg/m^2 . These trends highlight the ongoing rise in methane emissions and their potential impact on snow dynamics. In Figure 15b, the trend lines for nitrogen concentrations at Points 4 and 6 illustrate a consistent increase. Point 4 shows a monthly rise in nitrogen flux of 0.001 kg/m^2 , whereas Point 6 demonstrates a smaller increase of 0.0003 kg/m^2 . These upward trends in nitrogen emissions are significant for understanding the changing environmental conditions in the Ganges River basin. The mass fraction of CO_2 across 28 selected points in the Ganges River Basin, as depicted in Figure 15c, has steadily increased from 2003 to 2020, with a monthly rise of 0.0000003 kg/kg . This gradual increase aligns with broader trends of rising anthropogenic CO_2 emissions. Temperature trends also played a crucial role in snow dynamics in the Ganges River Basin. Figure 15d highlights rising maximum daily temperatures, with Point 5 and Point 9 showing increases of $0.0001\text{ }^{\circ}\text{C/day}$ and $0.0003\text{ }^{\circ}\text{C/day}$, respectively, from 1983 to 2023. Conversely, minimum temperatures have also risen, as shown in Figure 15e, with Point 5 and Point 6 increasing by $0.0003\text{ }^{\circ}\text{C/day}$ and $0.0002\text{ }^{\circ}\text{C/day}$, respectively. Temperature shifts play a crucial role in influencing both the rate of snowmelt and the stability of snow cover in the Ganges River Basin. Alongside rising temperatures, precipitation patterns have also changed. As illustrated in Figure 15f, there has been a marked decline in precipitation across the river basin between 1990 and 2019. Specifically, point 7 recorded a decrease of $0.0621\text{ mm per month}$, Point 3 showed a reduction of $0.0109\text{ mm per month}$ and Point 4 showed a reduction of $0.0014\text{ mm per month}$. These declines in precipitation, alongside rising temperatures and increasing greenhouse gas concentrations, highlight the intricate, interconnected climatic drivers reshaping snow cover dynamics and hydrological processes in the region.

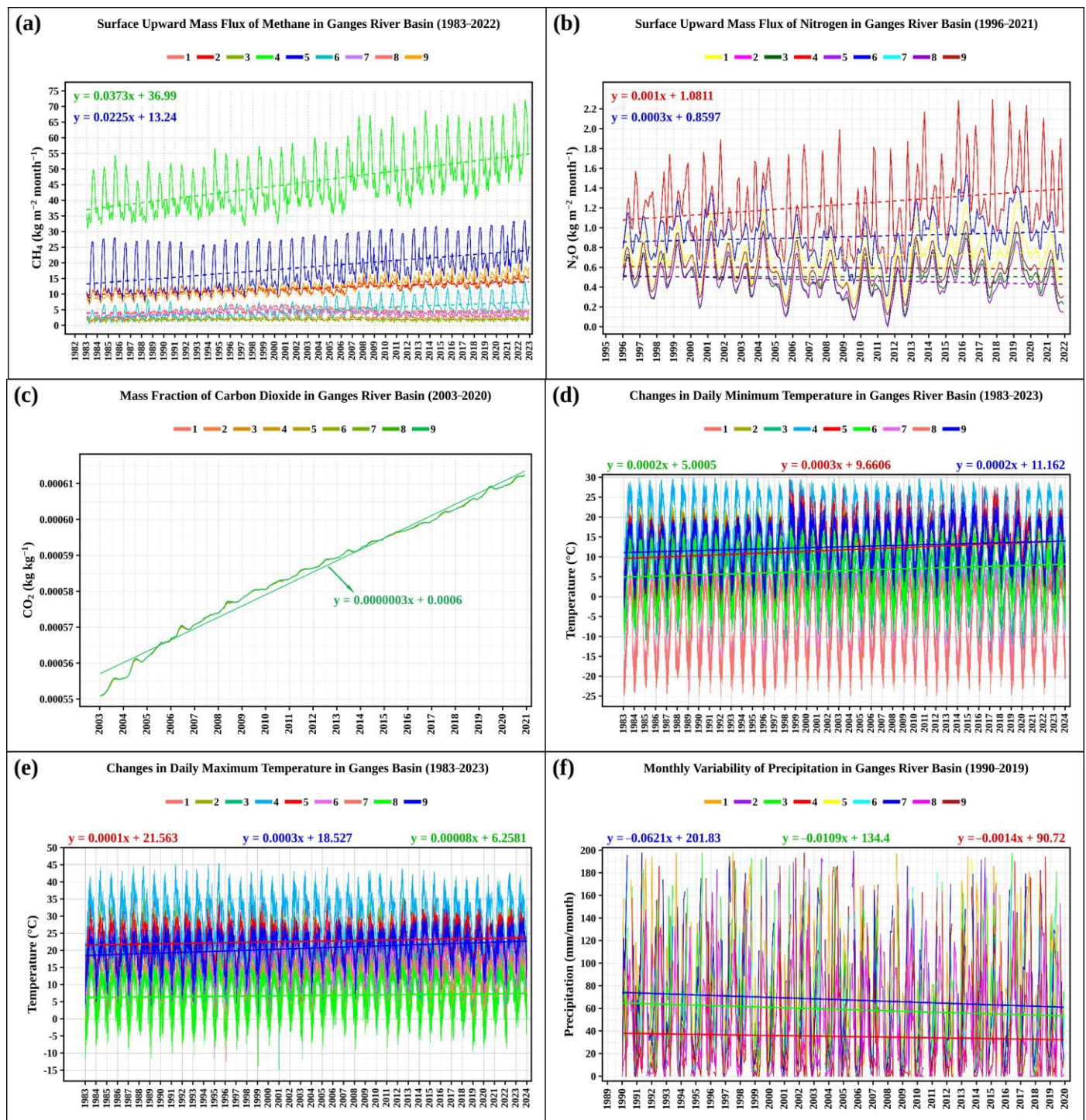


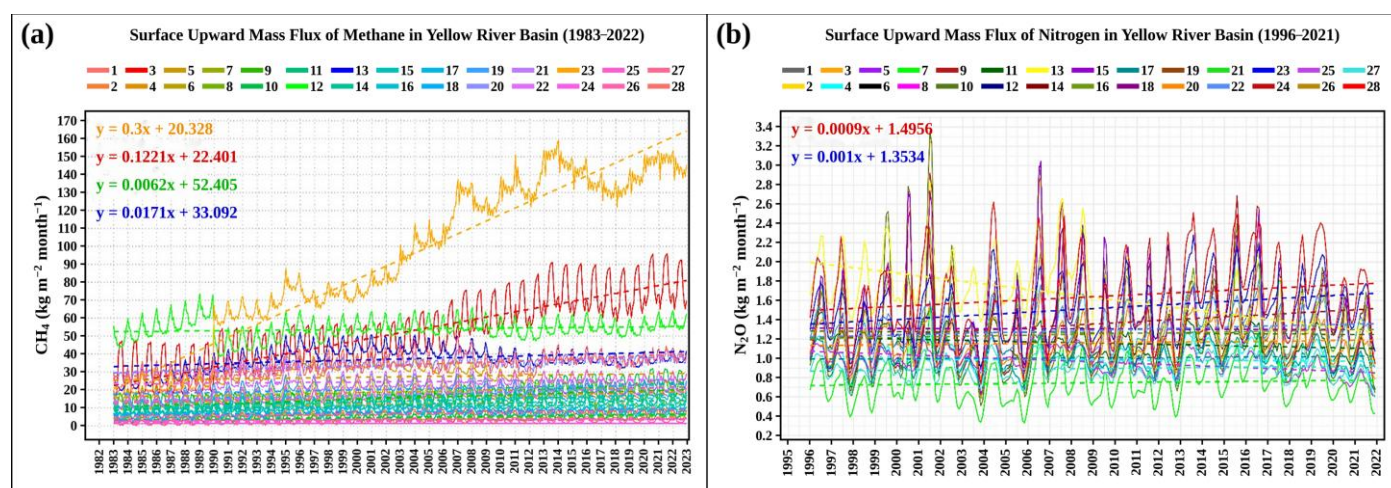
Figure 15. (a–f) Temporal trends of key climatic and environmental variables in the Ganges River basin: (a) methane flux (CH_4), (b) nitrogen flux (NO_x), (c) carbon dioxide (CO_2) mass fraction, (d) minimum temperature changes, (e) maximum temperature changes (f) monthly precipitation variability. Point numbers refer to the basin-localized subset of the 178 study points described in Section 2.1 and Figure 2.

3.2.7. Yellow River Basin (YRB)

The Yellow River Basin has shown a complex pattern of snow cover variability over the past few decades. Between 1993 and 1999, the river basin recorded a substantial increase in snow cover, averaging around 992.47 km^2 per year. This trend reversed from 2000 to 2011, with snow-covered areas decreasing by about 326.6 km^2 every six months. Interestingly, the most recent phase, from 2012 to 2023, shows a resurgence in snow cover,

with an average gain of 110.48 km² every three months. These fluctuations, especially the sharp decline observed in the early 2000s, are closely tied to the increasing presence of greenhouse gases such as methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O). These gases intensify the greenhouse effect by trapping heat in the atmosphere, altering snow accumulation patterns and accelerating snowmelt. The evolving relationship between emissions and snow dynamics has played a central role in shaping snow cover trends in the river basin. Supporting this, Figure 16a presents methane concentration trends at two monitored sites. Point 3 recorded a monthly increase of 0.1221 kg/m² in methane flux, while Point 23 showed an even more pronounced rise of 0.3 kg/m². These upward trends in methane levels reinforce the broader climatic changes impacting the region's snowpack and hydrological balance.

These trends highlight the ongoing rise in methane emissions and their potential impact on snow cover. In Figure 16b, the trend lines for nitrogen concentrations show a consistent increase over time. Point 23 shows a monthly rise in nitrogen mass flux of 0.001 kg/m², while Point 28 shows an increase of 0.0009 kg/m². These rising nitrogen emissions contribute to the changing environmental conditions in the Yellow River basin. The mass fraction of CO₂ across 28 selected points in the Yellow River basin has steadily increased from 2003 to 2020, as depicted in Figure 16c. The monthly rise in CO₂ mass fraction is 0.0000003 kg/kg, reflecting broader trends of increasing anthropogenic CO₂ emissions. Temperature trends also play a significant role in snow dynamics in the Yellow River Basin. Figure 16d highlights rising maximum daily temperatures, with Point 3 and Point 10 increasing by 0.0003 °C/day and 0.0002 °C/day, respectively, from 1983 to 2023. Minimum temperatures have also risen, as shown in Figure 16e, with Point 24 and Point 25 experiencing increases of 0.0002 °C/day and 0.0001 °C/day, respectively. These temperature changes are crucial as they impact snowmelt and snow cover stability. Precipitation trends in Figure 16f reveal increasing levels across the river basin. From 1990 to 2019, Point 15 increased by 0.0147 mm/month, point 21 increased by 0.023 mm/month, and Point 28 increased by 0.0301 mm/month. This increase in precipitation, combined with rising temperatures and greenhouse gas emissions, highlights the complex interplay of factors influencing snow dynamics in the Yellow River basin.



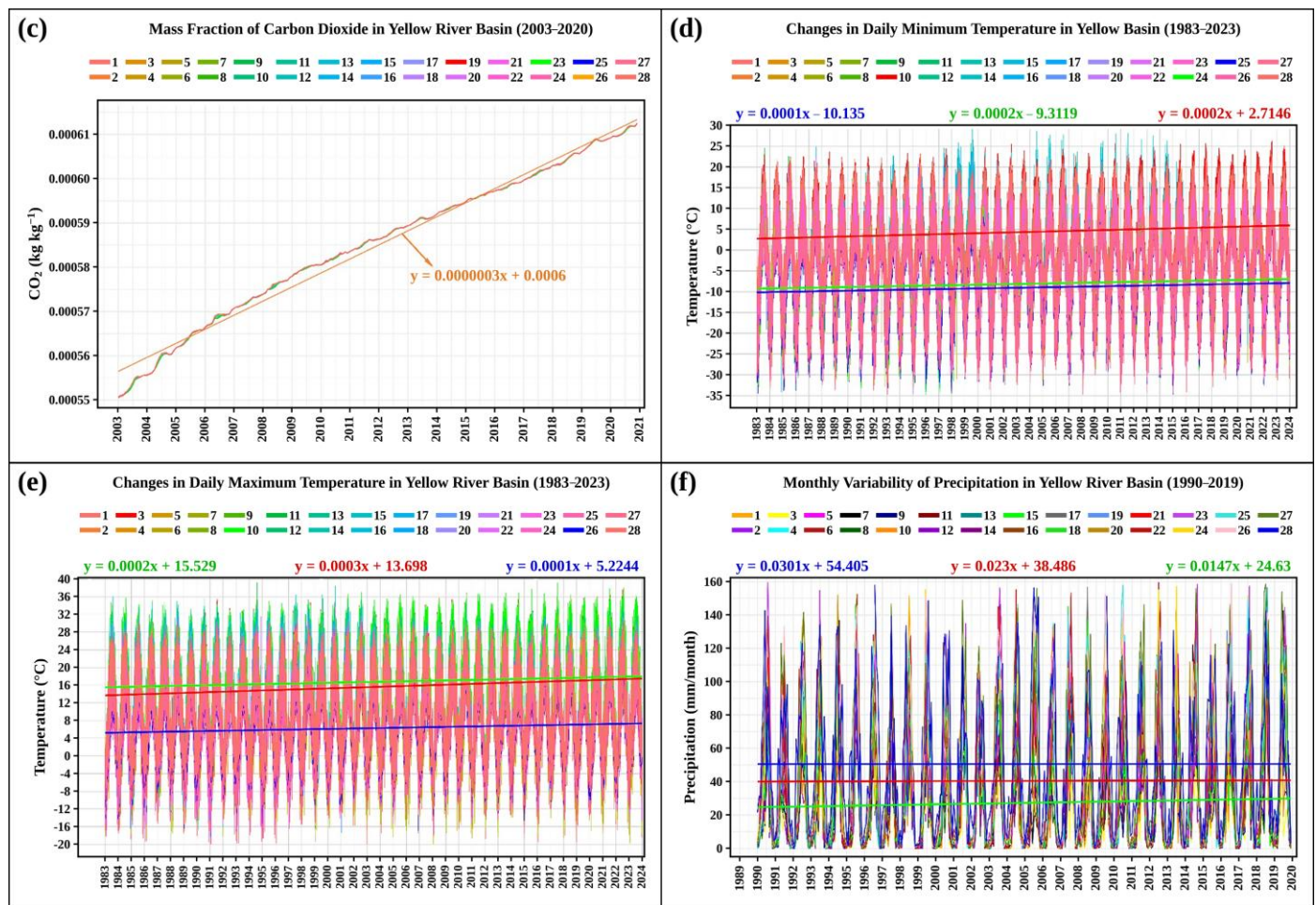


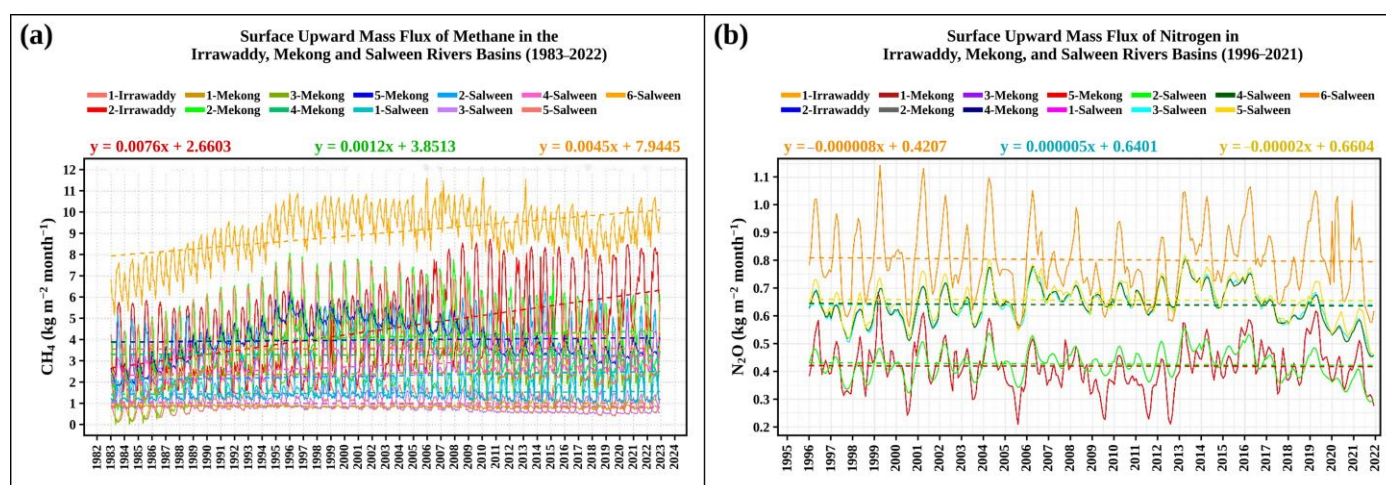
Figure 16. (a–f) Temporal trends of key climatic and environmental variables in the Yellow River basin: (a) methane flux (CH_4), (b) nitrogen flux (NO_x), (c) carbon dioxide (CO_2) mass fraction, (d) minimum temperature changes, (e) maximum temperature changes, (f) monthly precipitation variability. Point numbers refer to the basin-localized subset of the 178 study points described in Section 2.1 and Figure 2.

3.2.8. Irrawaddy, Mekong and Salween River Basins

Snow cover trends in the Irrawaddy, Mekong and Salween river basins reveal distinct patterns shaped by climatic factors such as greenhouse gas emissions, temperature rise and changes in precipitation. In the Irrawaddy River basin, snow cover varied between 1993 and 1999, with a modest annual increase of approximately 100.73 km². This was followed by a more consistent upward trend from 2000 to 2011, during which snow-covered areas expanded by about 244.8 km² every six months. However, the pattern reversed between 2012 and 2023, with snow cover declining at a rate of 124.05 km² every three months. These recent losses are closely linked to rising atmospheric concentrations of methane (CH_4) and carbon dioxide (CO_2), which intensify regional warming and accelerate snowmelt. The Mekong River basin has shown a more erratic snow cover pattern. Between 1993 and 1999, the river basin recorded a significant annual increase of roughly 1053.7 km². This trend reversed from 2000 to 2011, with snow cover declining by an average of 107.68 km² every six months. From 2012 to 2023, the rate of decline accelerated further, reaching 254.52 km² every three months. Elevated surface temperatures and increasing methane emissions appear to be the key contributors to this continued reduction in snow cover. In contrast, the Salween River basin experienced substantial snow accumulation between 1993 and 1999, with an average annual increase of 3863.8 km². This growth highlights the spatial variability of snow cover dynamics across

Southeast Asia's river basins and shows how local climate interactions can produce different responses, even within neighboring regions. Although the upward trend continued from 2000 to 2011, it slowed to 76.162 km² every six months. From 2012 to 2023, the snow cover increased by approximately 25.111 km² every three months. Despite the slow increase, the river basins' snow dynamics are still influenced by rising greenhouse gas emissions, particularly methane and nitrogen compounds, which affect snow accumulation and melting processes.

As depicted in Figure 17a, methane emissions have been increasing across the Irrawaddy, Mekong, and Salween river basins. Point 2-Irrawaddy experienced a monthly methane mass flux increase of 0.0076 kg/m², while Point 2-Mekong saw an increase of 0.0012 kg/m². Methane, a potent greenhouse gas, contributes significantly to regional warming and influences the rate of snowmelt in these river basins. Figure 17b illustrates nitrogen flux trends in these river basins. At Point 1 in the Irrawaddy river basin, a minor monthly decrease in nitrogen concentration (−0.000008 per month) was observed. However, in the Salween River basin, Point 3 showed a slight increase of 0.000005 per month, while Point 5 saw a steeper decline of −0.00002 per month. These changes in nitrogen levels contribute to the complex interactions between atmospheric chemistry and snow dynamics. The mass fraction of CO₂ has shown a consistent increase from 2003 to 2020 in all three river basins. The monthly rise in CO₂ mass fraction, shown in Figure 17c, is 0.0000003 kg/kg, further contributing to warming that accelerates snowmelt. Temperature trends have played a crucial role in snow dynamics within these river basins. Maximum temperatures at Point 1-Irrawaddy and Point 5-Mekong have gradually increased by 0.00001 °C/day and 0.0002 °C/day, respectively, from 1983 to 2023, as depicted in Figure 17d. Similarly, minimum temperatures at Point 5-Mekong and Point 5-Salween increased by 0.00005 °C/day and 0.00001 °C/day, respectively, as shown in Figure 17e. These rising temperatures directly influence snowmelt rates and snow cover reductions. Precipitation trends, as shown in Figure 17f, indicate increasing levels in the Irrawaddy River basin at Point 1 (0.0419 mm/month) and the Salween River basin at Point 3 (0.0282 mm/month), while the Mekong River basin at Point 2 experienced a decline in precipitation (0.0074 mm/month). Precipitation changes, coupled with rising temperatures, play a significant role in determining snow accumulation and snowmelt patterns in these river basins.



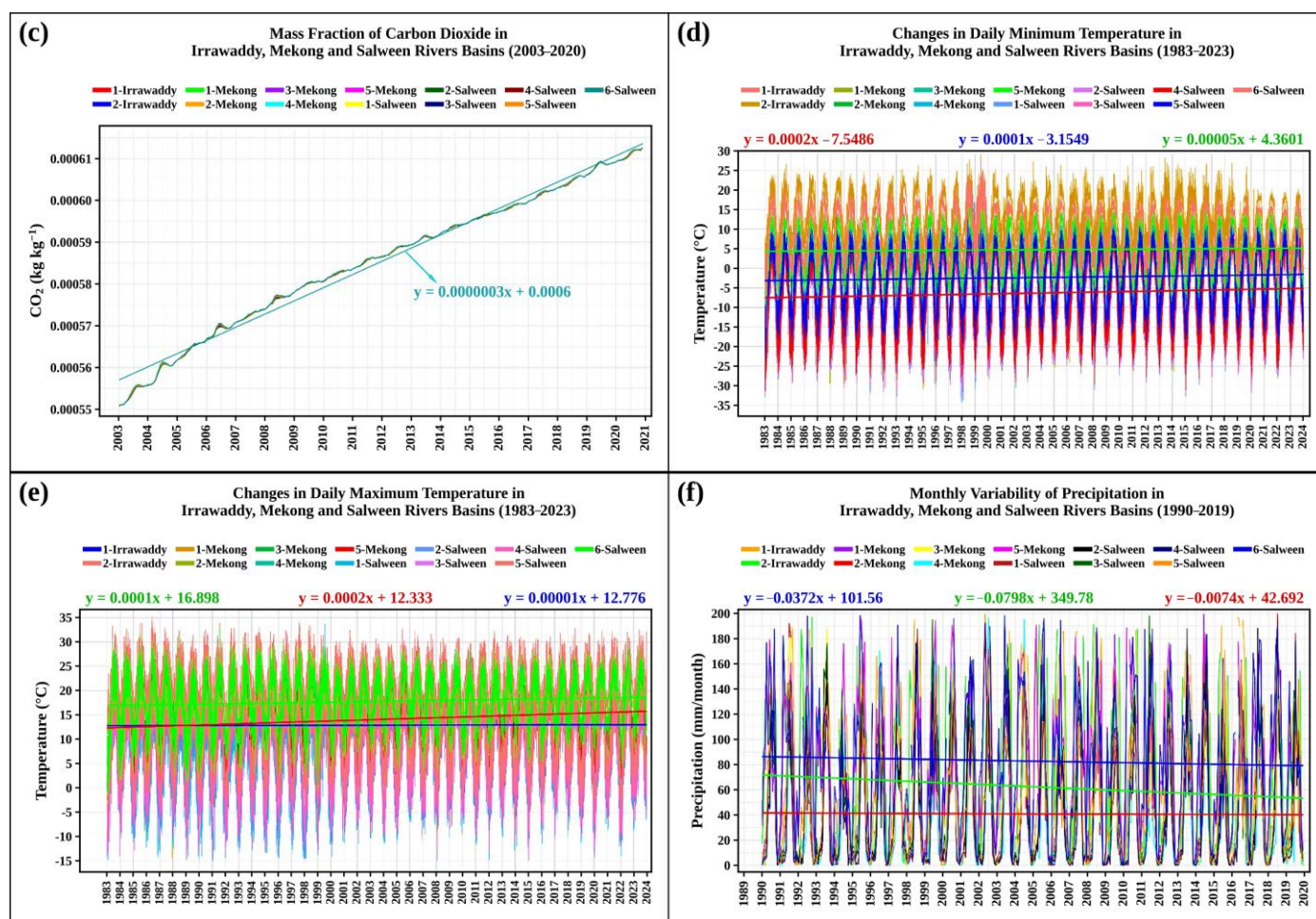


Figure 17. (a–f) Temporal trends of key climatic and environmental variables in the Irrawaddy, Mekong and Salween river basins: (a) methane flux (CH_4), (b) nitrogen flux (NO_x), (c) carbon dioxide (CO_2) mass fraction, (d) minimum temperature changes, (e) maximum temperature changes, (f) monthly precipitation variability. Point numbers refer to the basin-localized subset of the 178 study points described in Section 2.1 and Figure 2.

3.3. Discussion

In the Indus River Basin, analysis of Landsat time-series data revealed an average annual snow cover reduction of approximately 2108.86 km^2 . This long-term dataset provides a comprehensive view of snow cover dynamics and highlights the substantial environmental shifts occurring in the river basin, with far-reaching consequences for water availability and downstream ecosystems. In comparison, a study [1] reported higher annual snow cover losses, estimating declines of around 3358 km^2 per year using MOD09A1 data and 2459 km^2 per year using MOD09GA data during the 2008 to 2018 period. These estimates vary because of differences in temporal coverage, spatial resolution, and methodological frameworks. While MODIS data offers higher temporal frequency, allowing for continuous monitoring, Landsat's finer spatial resolution enables more accurate long-term assessments. Consequently, the Landsat-based results may yield more conservative estimates, capturing subtle yet persistent changes across the landscape. Nevertheless, both studies consistently indicate significant reductions in snow cover, highlighting the urgent need for continuous, high-resolution monitoring to inform water resource management and policy decisions. Numerous studies have reported a noticeable reduction in snow cover across the Himalayas [7,14] and the upper Indus River basin [52,53], which has primarily been linked to rising temperatures [54,55]. According to findings from the Global Land Ice Measurements from Space (GLIMS) initiative, the

extent of snow cover in the upper Indus River basin has shown a persistent downward trend [56]. Researchers [57] identified significant declines in snow coverage during the winter and autumn seasons within the catchment areas of the western tributaries of the Indus River. Similar declines in snow extent, driven by climatic shifts, have been documented in the Sutlej River basin [58] and the Kashmir region of the Himalayas [59,60].

In the Ganges and Brahmaputra river basins, this study identified annual decreases of 230.34 km² and 169.39 km², respectively, over the period of 1993–2023. In comparison, researchers [61] reported more subtle negative trends for 2000–2011, noting a maximum snow cover of 77.30% for the Ganges and 84.23% for the Brahmaputra during accumulation, which were reduced to 11.32% and 8.10% during ablation. The disparity in findings can be explained by differences in temporal scope and data resolution, with Landsat offering a more detailed depiction of sustained declines over three decades. The Brahmaputra river basin experienced an initial increase in snow cover between 1993 and 1999, followed by a pronounced decline beginning in 2012. This pattern closely resembles the trend observed in the Ganges River basin. Key climatic drivers behind these shifts include rising greenhouse gas emissions, elevated temperatures and declining precipitation, all of which highlight the growing vulnerability of these river basins. These changes highlight the need for adaptive strategies to manage water resources and preserve ecosystem integrity.

Similarly, the Yangtze River Basin has experienced a substantial reduction in snow cover over the past three decades. From 1993 to 1999, the river basin recorded an average annual increase of approximately 2242.8 km². However, this was followed by a steady decline between 2000 and 2011, averaging 523.49 km² every six months and an even sharper reduction from 2012 to 2023, with losses reaching 815.01 km² every three months. These findings are in line with observations by Wu et al. [62] who reported widespread snow mass decline across several western regions of China over the past 40 years. The persistent rise in greenhouse gas concentrations, coupled with warming temperatures and reduced precipitation, plays a central role in these transformations. Together, these factors underscore the importance of ongoing monitoring and adaptive water and land management practices to sustain hydrological stability and ecosystem resilience in the Yangtze River Basin.

In contrast, the Salween River Basin exhibited a notable increase in snow cover, averaging approximately 1002.66 km² per year. This atypical trend is largely attributed to the combined effects of the South Asian monsoon and mid-latitude westerlies, which enhance snowfall by increasing precipitation and promoting orographic uplift [63,64]. Additionally, increased winter precipitation in the Tibetan Plateau and cooler high-altitude temperatures contribute to prolonged snow accumulation and reduced melting [65]. Observations such as increasing precipitation at Point 3 (0.0282 mm/month from 1990 to 2019) further support this trend. The Yellow River and Irrawaddy river basins also showed modest increases in snow cover—147.06 km² and 20.86 km²/year, respectively. In the Yellow River basin, increased winter precipitation (e.g., 0.0147 mm/month at Point 15, 0.023 mm/month at Point 21, and 0.0301 mm/month at Point 28 from 1990 to 2019) and sustained cold temperatures at high altitudes contribute to this trend [31,66]. In the Irrawaddy River basin, localized climate conditions and the South Asian monsoon promote snowfall at higher altitudes [67,68], while relatively stable cold temperatures allow snow to accumulate and persist. Across all ten basins, the trends of climatic variables discussed above were derived from linear regression on each point's full-time series. Figures 10–17 are presented in their original form to document the complete observed record, including natural seasonal variability. A methodological limitation of this study is the use of identical SNOMAP threshold parameters across the Landsat 5, 7, 8, and 9 archives. While the use of Collection 2, Level 2 surface reflectance products for all

four sensors provides a consistent, cross-calibrated basis for this approach, small residual differences in sensor spectral response, particularly for the OLI sensor relative to TM/ETM+, cannot be fully ruled out. Future work incorporating sensor-specific threshold calibration, validated against independent high-resolution or ground-based snow cover observations during Landsat overlap periods, would help further constrain this source of uncertainty.

According to the latest climate commitments made during COP26, the global average temperature is projected to rise by approximately +2.7 °C [69]. This level of warming is anticipated to significantly amplify glacier melt, contributing an estimated 115 ± 40 mm sea level equivalent (SLE) to global sea level rise. Such a scenario could lead to the near-total disappearance of glaciers in several regions, including Central Europe, Western Canada and the United States, and New Zealand [70]. The impact of climate change on Himalayan glaciers is widely debated, as the IPCC report of 2007 suggested that Himalayan glaciers are likely to disappear by 2037. The Intergovernmental Panel on Climate Change (IPCC) has projected that warming will be most pronounced in the higher latitudes of the Northern Hemisphere, which is expected to reduce snow coverage drastically [71]. Furthermore, the IPCC highlights that Himalayan snowpacks are receding more rapidly than those in other global mountain ranges, and this accelerated glacial thinning may eventually convert the Indus, Ganges, and Brahmaputra rivers into seasonal waterways [72,73]. Beyond the regional perspective, global glaciers have retreated, which highlights the severity of climate change impacts. The Pizol Glacier in eastern Switzerland (Glarus Alps) has lost over 80% of its volume since 2006 and was declared dead in 2019 [74]. Similarly, the Okjökull Glacier in Iceland, once part of the Langjökull Glacier, lost its glacier status in 2014 due to significant ice loss [75]. In Italy, the Calderone Glacier in the Apennine Mountains has drastically retreated over the past century. Once considered the southernmost glacier in Europe, it has significantly diminished in size and could disappear entirely within a few decades if current trends continue [76]. Additionally, the Lyell Glacier in Yosemite National Park, USA, has nearly disappeared. Once a prominent feature of the Sierra Nevada, it has shrunk considerably, highlighting the broader trend of glacial retreat in North America [77]. If current climate trends persist, the snow cover and glaciers in the Hindu Kush Himalaya (HKH) river basins may face severe depletion. The loss of these vital ice reserves would have profound implications for regional water security. Snow- and glacier-fed rivers such as the Amu Darya, Indus, Ganges and Brahmaputra support the livelihoods of millions. A reduction in glacial contributions would intensify water scarcity, compromise food security and heighten the potential for transboundary water conflicts. These findings highlight the urgent need for river basin-specific adaptation strategies to address rapid cryospheric changes. Future research must integrate high-resolution climate projections and enhanced glacier monitoring to support data-driven water management. Regional and international cooperation will be crucial in mitigating the impacts of climate change on glacier-fed systems and safeguarding the fragile mountain ecosystems and communities that rely on them.

4. Conclusions

This study highlights the substantial influence of climate change on snow cover dynamics within the Hindu Kush-Himalayan (HKH) region. Using Landsat imagery, the study provides a comprehensive analysis of snow cover variability over the past three decades across the basins of 10 snow- and rainfall-dominated major rivers. The findings reveal a widespread decline in snow cover in the Amu Darya, Indus, Tarim, Yangtze, and Ganges river basins, with annual declines of 2793.15, 2108.86, 1013.09, 1199.49, and 230.34 km². The Mekong and Brahmaputra river basins showed moderate decreases of 247.51

and 169.39 km² per year. In contrast, the Salween River basin revealed a significant increase in snow cover of approximately 1002.66 km² per year. The Yellow River and Irrawaddy river basins also exhibited a minor increase in snow cover area of 147.06 and 20.86 km² per year, respectively. These observed trends are strongly associated with higher concentrations of greenhouse gas emissions, rising surface temperatures, and shifts in precipitation regimes, all of which significantly alter snow accumulation and melt processes. The study highlights the critical importance of snow cover supporting agriculture and enabling hydropower production in downstream regions. Continued reductions in snowpack across key river basins may pose serious risks to water availability for the millions of people that are dependent on these rivers. These findings emphasize the need for robust snow monitoring to support preservation systems that buffer against climate change effects through long-term cryospheric preservation strategies. It should be noted that this analysis relied on satellite imagery, which is limited by cloud cover, terrain effects in the steep and complex topography of the HKH region, and the spatial resolution of the Landsat sensors used; the 178-point sampling framework, while enabling correlation with hydrometeorological variables, represents a targeted subset rather than a fully continuous basin-wide validation. Despite these limitations, the consistent multi-decadal trends observed across multiple satellite supports the reliability of the reported patterns. From a water-resources perspective, the widespread snow-cover decline identified in the Amu Darya, Indus, Tarim, Yangtze, and Ganges basins carries direct implications for downstream irrigation supply, hydropower generation, and water-sector planning, and highlights the need for adaptive water-management strategies in these basins. Future work should be focused on extending these findings by coupling the observed snow-cover trends with hydrological models to quantify downstream runoff impacts, and by incorporating higher-resolution or radar-based satellite data to improve retrieval accuracy in cloud-prone and topographically complex areas of the HKH region.

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