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Monitoring Snow-Covered Dynamics and Impact on Climatic Change

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Glaciated areas play a crucial role in cooling the planet; however, their accelerated melting initiates a feedback loop that decreases Earth's albedo, leading to further warming and increased melting. This phenomenon poses significant risks to Pakistan's agricultural productivity and energy supply, particularly in the Himalayan, Karakoram, and Hindukush (HKH) mountain ranges. These regions are undergoing substantial changes due to global warming and regional climate variability. Glaciers and snowpacks in these areas function as natural reservoirs, releasing vital meltwater during the summer to sustain river flows, especially the Indus River, which is essential for Pakistan's agriculture, drinking water, and hydropower. This study aims to monitor the extent, mass, and distribution of snow cover in the HKH ranges to assess local vulnerability and provide a comprehensive evaluation of ongoing climate change impacts. By analyzing Landsat 5, 7, and 8's Tier 1 Top of Atmosphere (TOA) reflectance products, the annual median snow cover from 1991 to 2020 was calculated to visualize and quantify snow cover dynamics in Hunza Nagar, Gilgit-Baltistan, Pakistan. The results revealed no significant trends in total snow cover, with only minor fluctuations and variations from the mean value, and notable reductions during strong El Niño years. These findings underscore the critical importance of glaciated areas and the threats posed by their melting. Ongoing monitoring and comprehensive regional assessments are vital to understanding the impacts of climate change on snow cover dynamics. Such efforts are essential for developing adaptive strategies to mitigate adverse effects on Pakistan's water resources, agriculture, and energy systems.

Keywords: Global warming, Normalized Difference Snow Index, El Nino, La Nino, El Nino Southern Oscillation, Microclimate.

Introduction:

Precipitation that forms when water vapor freezes is known as snow [1]. Snow is highly reflective, with new snow having an albedo of 0.8–0.9, meaning it reflects 80–90% of incoming solar energy [2][3][4]. This high reflectivity plays a crucial role in climate regulation by reflecting sunlight back into space, thereby cooling the planet. Additionally, snow supports various ecological functions; its melting provides essential water for drinking, irrigation, and soil moisture, and helps reduce wildfire risks [5]. However, excessive snow accumulation can lead to springtime flooding when it melts. While snow and ice cover the Earth's Polar Regions year-round, coverage at lower latitudes varies with season and elevation [6]. High-altitude regions such as the Tibetan Plateau, the Andes, the Rocky Mountains, and the Himalayas retain some snow cover nearly year-round [7].

Pakistan's agriculture-dependent economy relies heavily on runoff from snow and glaciers in Northern Pakistan [8]. During winter, western depressions contribute to snow cover in the HKH ranges, which, upon melting in the summer, feeds the rivers vital for the country's water supply, hydropower generation, and irrigation [9]. This runoff is crucial for millions of people and helps manage resource distribution. However, snow cover is highly sensitive to climate change and global warming, making it essential to assess and quantify the impacts of climate variability on regional snow cover [10].

Snow cover dynamics significantly affect hydrological patterns, biodiversity, and tourism in northern Pakistan, influencing both seasonal and annual snow accumulation and depletion [11]. This study aims to understand the impact of climate change on snow cover in Hunza Nagar by analyzing Landsat 5, 7, and 8 satellite data from 1991 to 2020. Using Google Earth Engine, the study visualized and analyzed spatio-temporal changes in snow cover. The findings indicate that, on average, 67-71% of Hunza Nagar's area was covered in snow from 1991 to 2020, with notable declines during El Niño years and partial recovery during La Niña years.

The study provides critical data on snow cover dynamics in Pakistan's HKH mountain ranges, which are vital for the country's water security, agriculture, and energy generation. Monitoring snow cover from 1991 to 2020 reveals significant vulnerabilities and fluctuations, particularly during strong El Niño events. These results highlight the importance of continuous monitoring and regional assessments to develop adaptive strategies for managing water resources, agriculture, and energy systems amidst climate variability.

The accelerated melting of glaciers and snow cover in the HKH ranges due to global warming and regional climate variability poses severe threats to Pakistan's water security, agricultural productivity, and energy resources [12]. The current understanding of snow cover dynamics is limited, complicating efforts to assess vulnerability and develop effective adaptation strategies. The absence of comprehensive, long-term data hinders the ability to predict water availability and manage resources sustainably. Therefore, it is crucial to monitor and analyze snow cover dynamics in the HKH ranges to provide a detailed assessment of climate change impacts and support adaptive strategies. The primary objective of this study is to assess and analyze snow cover dynamics in Hunza Nagar, Gilgit-Baltistan, from 1991 to 2020, using the Normalized Difference Snow Index (NDSI) calculated through Google Earth Engine. The study aims to monitor changes in snow cover patterns, identify trends and fluctuations, and compare annual snow cover during El Niño, La Niña, and neutral years, while exploring the influence of global meteorological conditions on local snow cover dynamics.

Aims and Objectives:

The main objectives of this study are:

- To calculate and visualize the Normalized Difference Snow Index (NDSI) using the Google Earth Engine (GEE) code editor, isolate snow-covered areas from non-snow-covered areas, and determine the extent in square kilometers.

- To monitor changes in snow cover patterns in Hunza Nagar over a period of three decades (1991-2020).
- To observe and compare variations in the total annual snow-covered area during El Niño, neutral, and La Niña years.
- To interpret the relationship between global meteorological conditions and their impact on the local meteorological conditions of Hunza Nagar.

Study Area:

The study was conducted in Hunza Nagar (comprising Hunza and Nagar districts) in Gilgit-Baltistan, Pakistan. This region extends from 36° 0' 15.92" N to 37° 5' 21.93" N latitude and 74° 2' 40.18" E to 76° 3' 43.33" E longitude, covering an area of 14,312 square kilometers. Hunza and Nagar, which were declared separate districts in 2015, are the northernmost districts of Pakistan. They are bordered by Ishkoman to the west, Shigar to the southeast, Afghanistan's Wakhan Corridor to the northwest, and China's Xinjiang region to the northeast (see Figure 1).

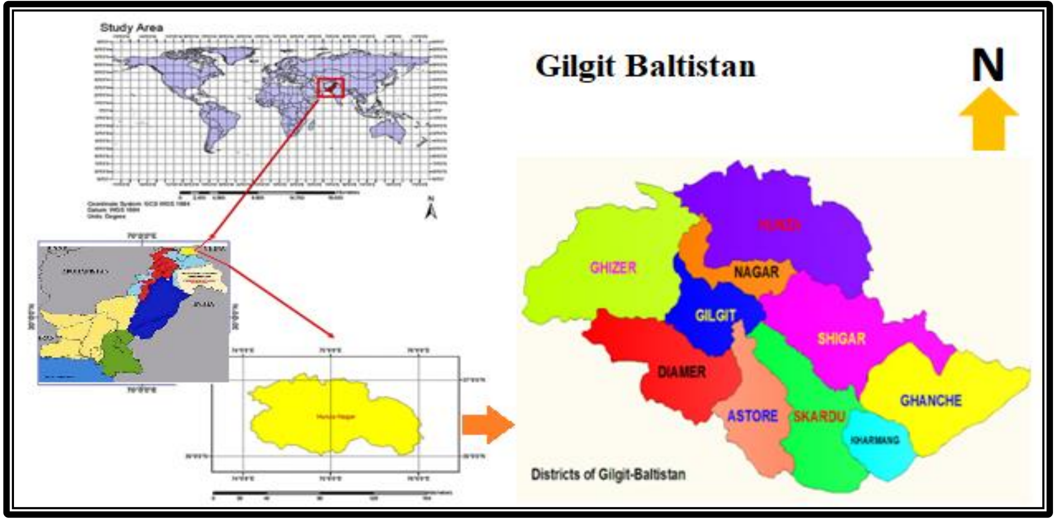


Figure 1: Location Map of the Study Area

Study Area in the Context of Regional Climate:

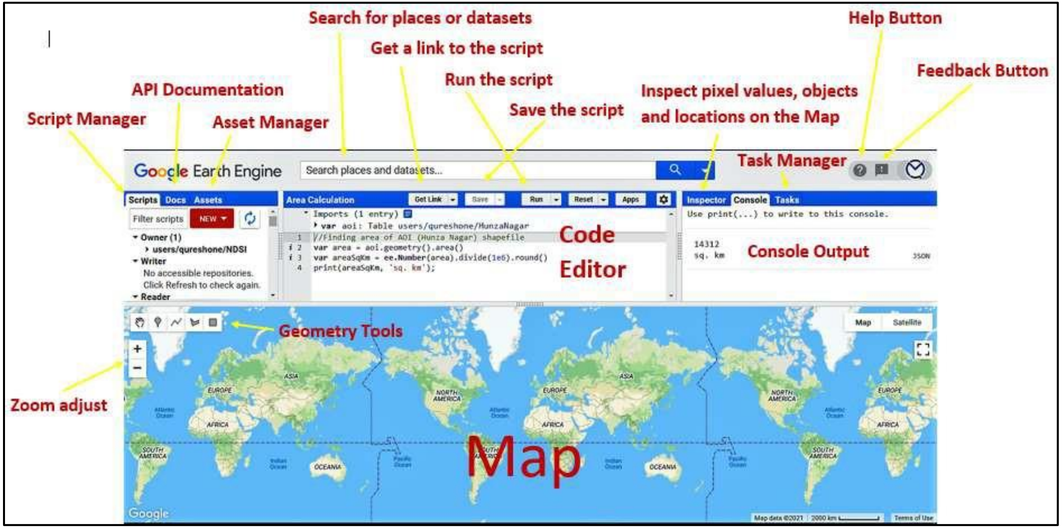
The climate of Northern Pakistan, including Hunza Nagar, is significantly shaped by the presence of three major mountain systems: the Himalayas to the east, the Hindukush to the west, and the Karakoram to the north, which together span over 2,000 kilometers. This mountainous region exhibits high variability in climate, largely governed by microclimates [13]. The presence of rain shadows and varying precipitation levels contribute to this variability. The moist temperate zone of the western Himalayas decreases as one moves northwest towards the drier Karakoram and Hindukush ranges. These mountain ranges from a natural barrier between the monsoon-influenced areas of South Asia to the south and the vast deserts of Central Asia to the north [14]. As a result, during summer, the region is influenced by remnants of the monsoon system from the south. In winter and spring, it is affected by westerly depressions originating from the Mediterranean and Caspian Seas. Even in summer, higher elevations occasionally experience precipitation from these westerly air masses. When monsoon systems extend this far north, they can bring significant precipitation during the summer months [15].

Methods and Materials:

Google Earth Engine (GEE):

The Google Earth Engine (GEE) platform was utilized to conduct a geospatial analysis of the Hunza Nagar region (Figure 2). A moderately complex code was developed and executed to extract, compute, map, and monitor snow cover dynamics in the study area from 1991 to 2020. GEE offers access to extensive, historic, near-real-time, and real-time satellite data and scientific measurements through cloud technology, enabling impressive computational speeds.

Its web-based integrated development environment provides users with rapid access to vast Earth data stores, facilitating geospatial analyses to detect changes, map trends, and quantify differences on the Earth's surface without the need for local storage or software maintenance. GEE applications include deforestation detection, land cover classification, forest biomass and carbon estimation, and mapping of the world's roadless areas.



```
Imports (1 entry)
  var aoi: Table users/qureshone/HunzaNagar
//Finding area of AOI (Hunza Nagar) shapefile
var area = aoi.geometry().area()
var areaSqKm = ee.Number(area).divide(1e6).round()
print(areaSqKm, 'sq. km');
```

```
Use print(...) to write to this console.
14312
sq. km
```

Figure 2: Components of Google Earth Engine interface and Code Editor window

Table1: Landsat 5 Thematic mapper (TM)

Landsat 5	Wavelength (Micro meters)	Resolution (meters)
Band 1	0.45-0.52	30
Band 2	0.52-0.60	30
Band 3	0.63-0.69	30
Band 4	0.76-0.90	30
Band 5	1.55-1.75	30
Band 6	10.40-12.50	120 (30)
Band 7	2.08-2.35	30

Courtesy: USGS

Landsat Sensors:

For this study, Landsat data was utilized to monitor and calculate snow-covered areas over different time periods: Landsat 5 data from 1991 to 1999, Landsat 7 data from 2000 to 2013, and Landsat 8 data from 2014 to 2020. The Thematic Mapper (TM) sensor on Landsat 5 collected data across four spectral ranges, similar to the Multi-Spectral Scanner of earlier Landsat satellites, while also introducing thermal and shortwave infrared bands. Landsat 7's Enhanced Thematic Mapper Plus (ETM+) sensor added a panchromatic band. Landsat 8, equipped with the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS), acquires data across 11 bands. Detailed information is provided in Tables 1, 2, and 3.

Table 2: Landsat 7 Enhances Thematic Mapper Plus (ETM+)

Landsat 7	Wavelength (Micro meters)	Resolution (meters)
Band 1	0.45-0.52	30
Band 2	0.52-0.60	30
Band 3	0.63-0.69	30
Band 4	0.76-0.90	30
Band 5	1.55-1.75	30
Band 6	10.40-12.50	60 (30)
Band 7	2.09-2.35	30
Band 8	.52-.90	15

Courtesy: USGS

Table 3: Landsat 7 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)

Bands	Wavelength (Micro meters)	Resolution (meters)
Band 1 – Coastal aerosol	0.43-0.45	30
Band 2 – Blue	0.45-0.51	30
Band 3 – Green	0.53-0.59	30
Band 4 – Red	0.64-0.67	30
Band 5 – Near Infrared (NIR)	0.85-0.88	30
Band 6 – SWIR 1	1.57-1.65	30
Band 7 – SWIR 2	2.11-2.29	30
Band 8 – Panchromatic	0.50-0.68	15
Band 9 – Cirrus	1.36-1.38	30
Band 10 – Thermal Infrared (TIRS) 1	10.6-11.19	100
Band 11 - Thermal Infrared (TIRS) 2	11.50-12.51	100

Courtesy: USGS

Normalized Difference Snow Index – NDSI:

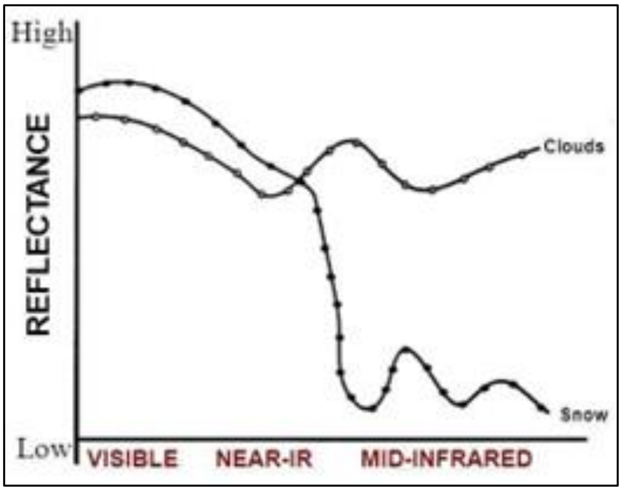


Figure 3: Spectral Reflectance of snow vs. clouds

The Normalized Difference Snow Index (NDSI) was applied following the method proposed by Hall et al. (1995) [16]. This index works by normalizing the difference between the green band and the shortwave infrared (SWIR) band. Hall et al. (1995) [16] developed a snow-mapping algorithm that served as the foundation for the MODIS standard snow-mapping product. NDSI is a numerical indicator used to identify snow cover over land areas. It utilizes the green and SWIR spectral bands to map snow cover, as snow absorbs most incident radiation in the SWIR band, unlike clouds, which allows NDSI to effectively differentiate snow from clouds. Further details are provided in Figure 3.

Formula of NDSI = (Green - SWIR) / (Green + SWIR)

NDSI (Landsat 8) = (B3 – B6) / (B3 + B6) **1**

NDSI (Landsat 5 and 7) = (B2 – B5) / (B2 + B5) **2**

The methodology employed in this study to determine the snow cover dynamics and snow-covered area of Hunza Nagar from 1991 to 2020 is outlined as follows:

- An annual median raster for each year from 1991 to 2020 was utilized to extract and visualize Landsat scenes.
- To analyze the spatial and temporal patterns of snow cover, the study used a collection of nine Landsat 5 TM images (1991-1999), fourteen Landsat 7 ETM+ images (2000-2013), and seven Landsat 8 OLI/TIRS images, all in digital format with a spatial resolution of 30 meters.

- The Hunza Nagar study area was clipped using its shapefile from the Landsat scenes and visualized using false-color composites to highlight snow-covered areas against vegetation, water, and rocky mountainous regions. For Landsat 5 and 7, the band combination used was 5, 4, 3, while for Landsat 8, the band combination was 6, 5, 4. Further details are provided in Figure 4.

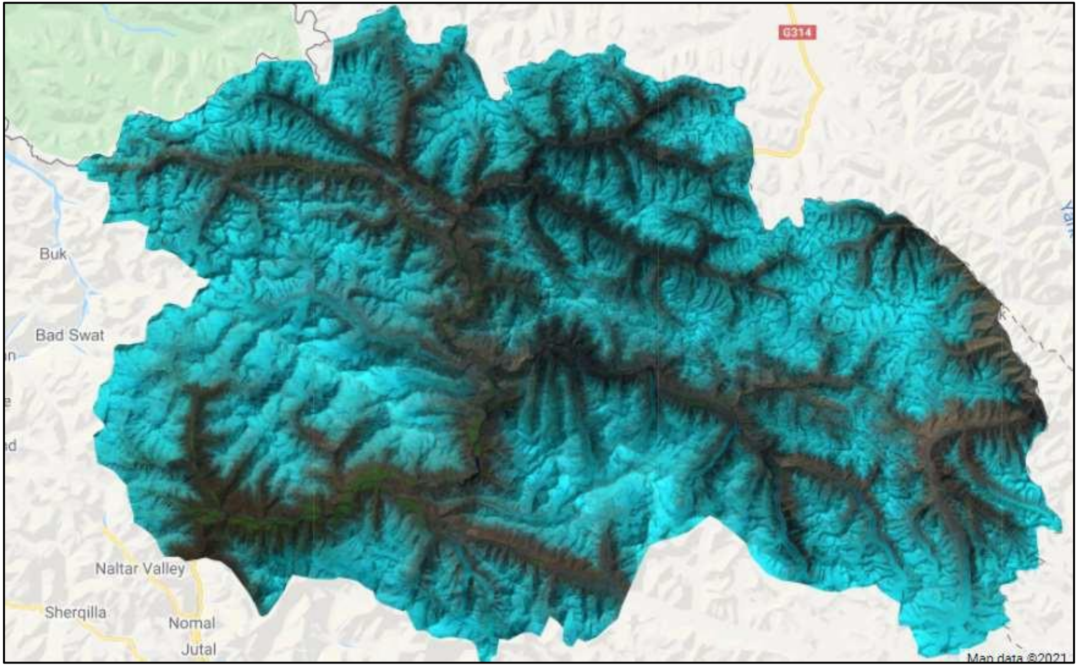


Figure 4: Clipped False Color Composite of Hunza Nagar (2020 annual median)

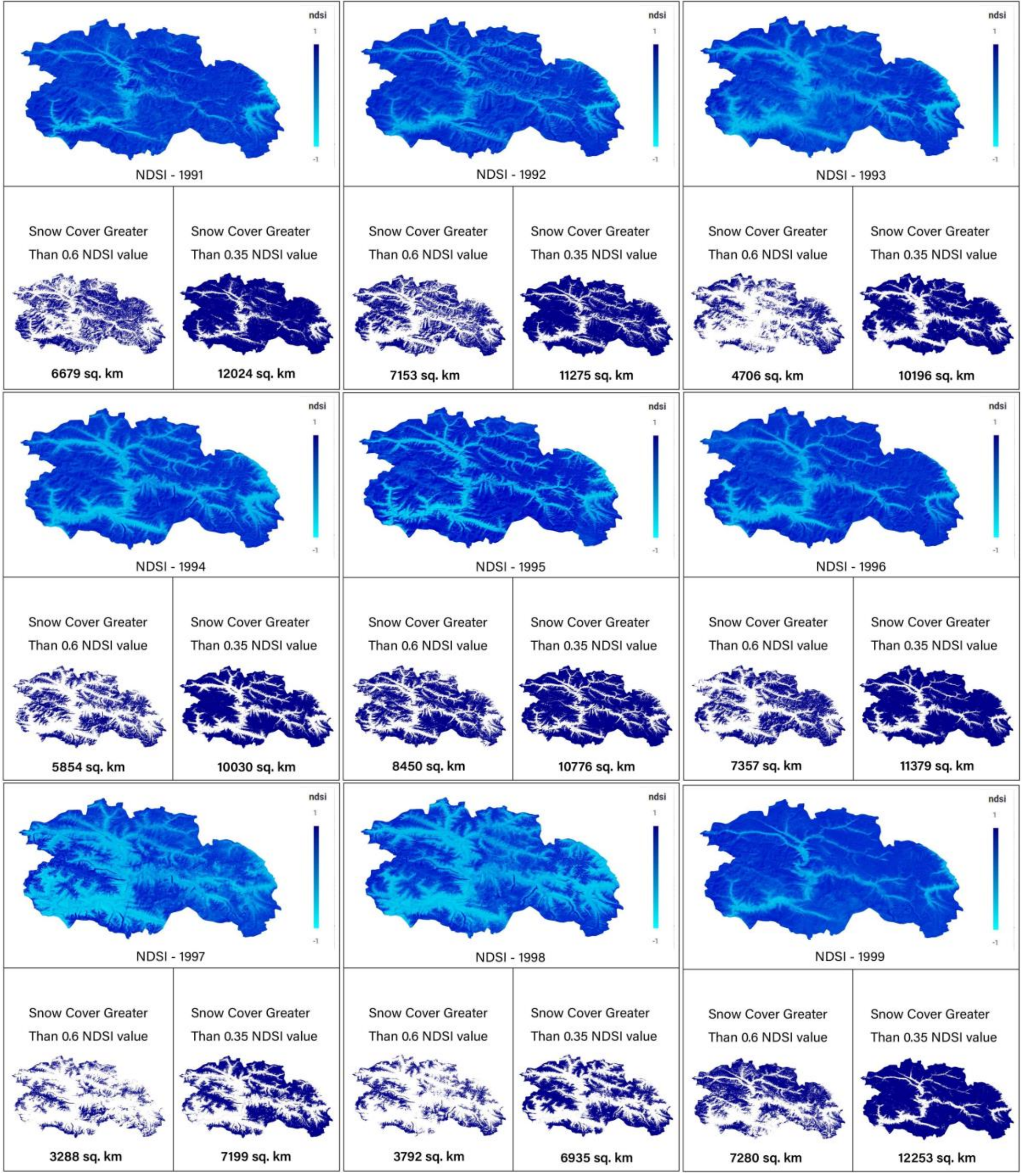
Results:

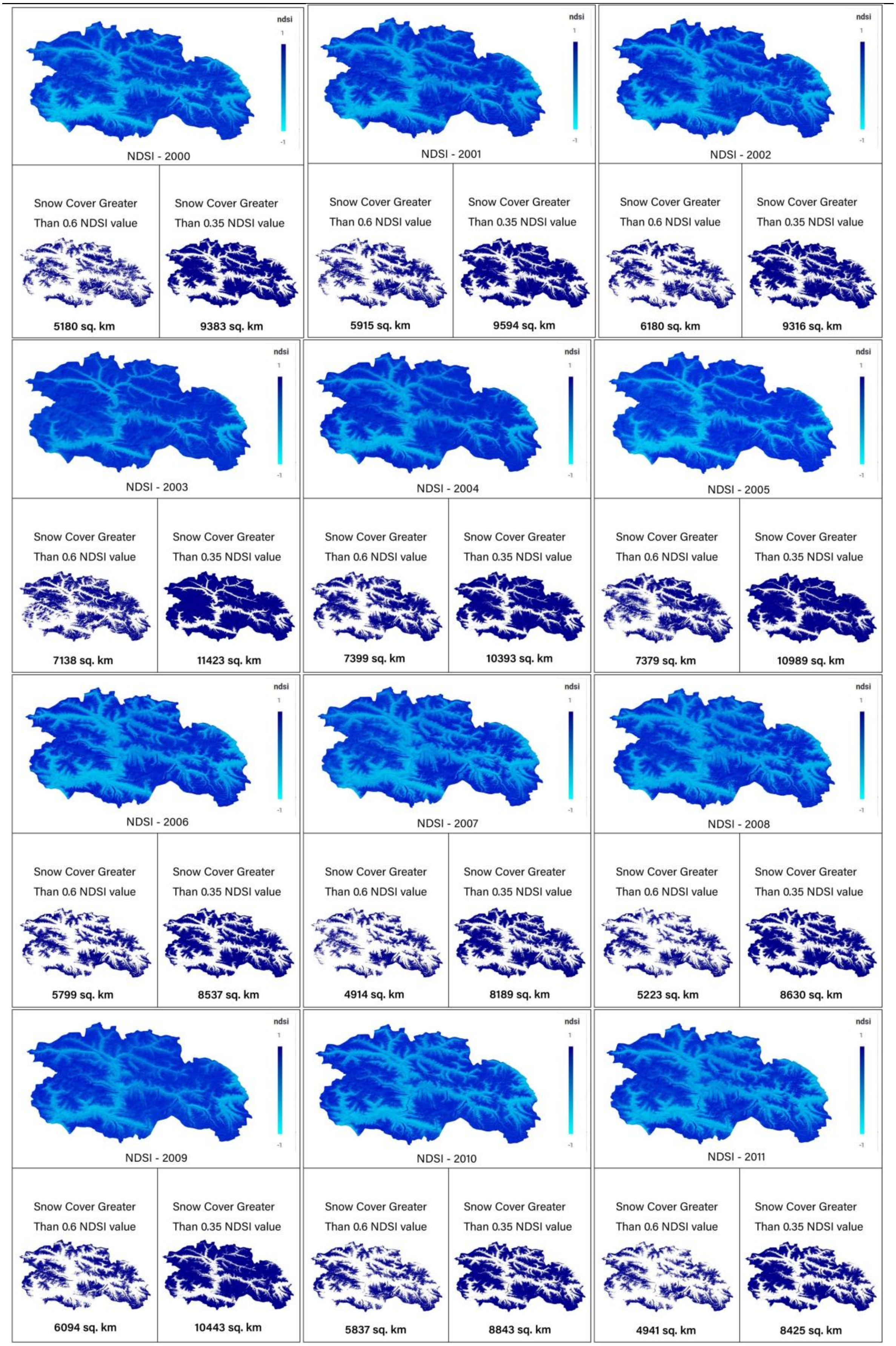
The NDSI rasters for each year from 1991 to 2020 were processed according to the snow classification criteria established by Hall et al. (1995, 1998) to determine the snow-covered area in square kilometers. The NDSI thresholds were set at >0.6 and >0.35 to account for various types of snow and frost. Specifically, an NDSI value greater than 0.6 was used to identify fresh, coarse, and fine-grained snow, which has relatively high spectral reflectance. An NDSI value greater than 0.35 was used to account for frost, which has relatively lower spectral reflectance and may include rock debris, vegetation, and other elements. Snow was classified into categories based on spectral reflectance ranges: coarse granular snow (>0.937), medium granular snow (0.848 to 0.937), fine granular snow (0.611 to 0.848), and frost (0.414 to 0.611), with pixels exceeding an NDSI value of 0.6 classified as snow and those with an NDSI value greater than 0.35 classified as frost.

Table 4: Details of Snow Cover Greater Than 0.35 NDSI value

Year	Snow Covered Area	(Total area: 14312 sq. km)
1991	12024 sq. km	84.0% of total
1996	11379 sq. km	79.5% of total
2001	9594 sq. km	67.0% of total
2006	8537 sq. km	59.6% of total
2011	8425 sq. km	58.8% of total
2016	10150 sq. km	70.9% of total
2020	9918 sq. km	69.2% of total

The analysis revealed that while some areas of Gilgit Baltistan have experienced a decline in total snow cover, Hunza Nagar exhibited fluctuations in snow cover with no significant long-term trend of increase or decrease over the three decades. On average, 67-71% of Hunza Nagar has remained covered with snow from 1991 to 2020, with notable declines during El Niño years. This decline in snow cover appears to have been offset during La Niña years, indicating a rebound as El Niño effects subside. The GeoTIFF rasters displaying NDSI results for each year and the total snow-covered area at the 0.6 and 0.35 threshold values are presented in Figures 5 and 6, and Tables 4 and 5.




ndsi
1
-1
NDSI - 2000
Snow Cover Greater Than 0.6 NDSI value
5180 sq. km
Snow Cover Greater Than 0.35 NDSI value
9383 sq. km
NDSI - 2001
Snow Cover Greater Than 0.6 NDSI value
5915 sq. km
Snow Cover Greater Than 0.35 NDSI value
9594 sq. km
NDSI - 2002
Snow Cover Greater Than 0.6 NDSI value
6180 sq. km
Snow Cover Greater Than 0.35 NDSI value
9316 sq. km
NDSI - 2003
Snow Cover Greater Than 0.6 NDSI value
7138 sq. km
Snow Cover Greater Than 0.35 NDSI value
11423 sq. km
NDSI - 2004
Snow Cover Greater Than 0.6 NDSI value
7399 sq. km
Snow Cover Greater Than 0.35 NDSI value
10393 sq. km
NDSI - 2005
Snow Cover Greater Than 0.6 NDSI value
7379 sq. km
Snow Cover Greater Than 0.35 NDSI value
10989 sq. km
NDSI - 2006
Snow Cover Greater Than 0.6 NDSI value
5799 sq. km
Snow Cover Greater Than 0.35 NDSI value
8537 sq. km
NDSI - 2007
Snow Cover Greater Than 0.6 NDSI value
4914 sq. km
Snow Cover Greater Than 0.35 NDSI value
8189 sq. km
NDSI - 2008
Snow Cover Greater Than 0.6 NDSI value
5223 sq. km
Snow Cover Greater Than 0.35 NDSI value
8630 sq. km
NDSI - 2009
Snow Cover Greater Than 0.6 NDSI value
6094 sq. km
Snow Cover Greater Than 0.35 NDSI value
10443 sq. km
NDSI - 2010
Snow Cover Greater Than 0.6 NDSI value
5837 sq. km
Snow Cover Greater Than 0.35 NDSI value
8843 sq. km
NDSI - 2011
Snow Cover Greater Than 0.6 NDSI value
4941 sq. km
Snow Cover Greater Than 0.35 NDSI value
8425 sq. km

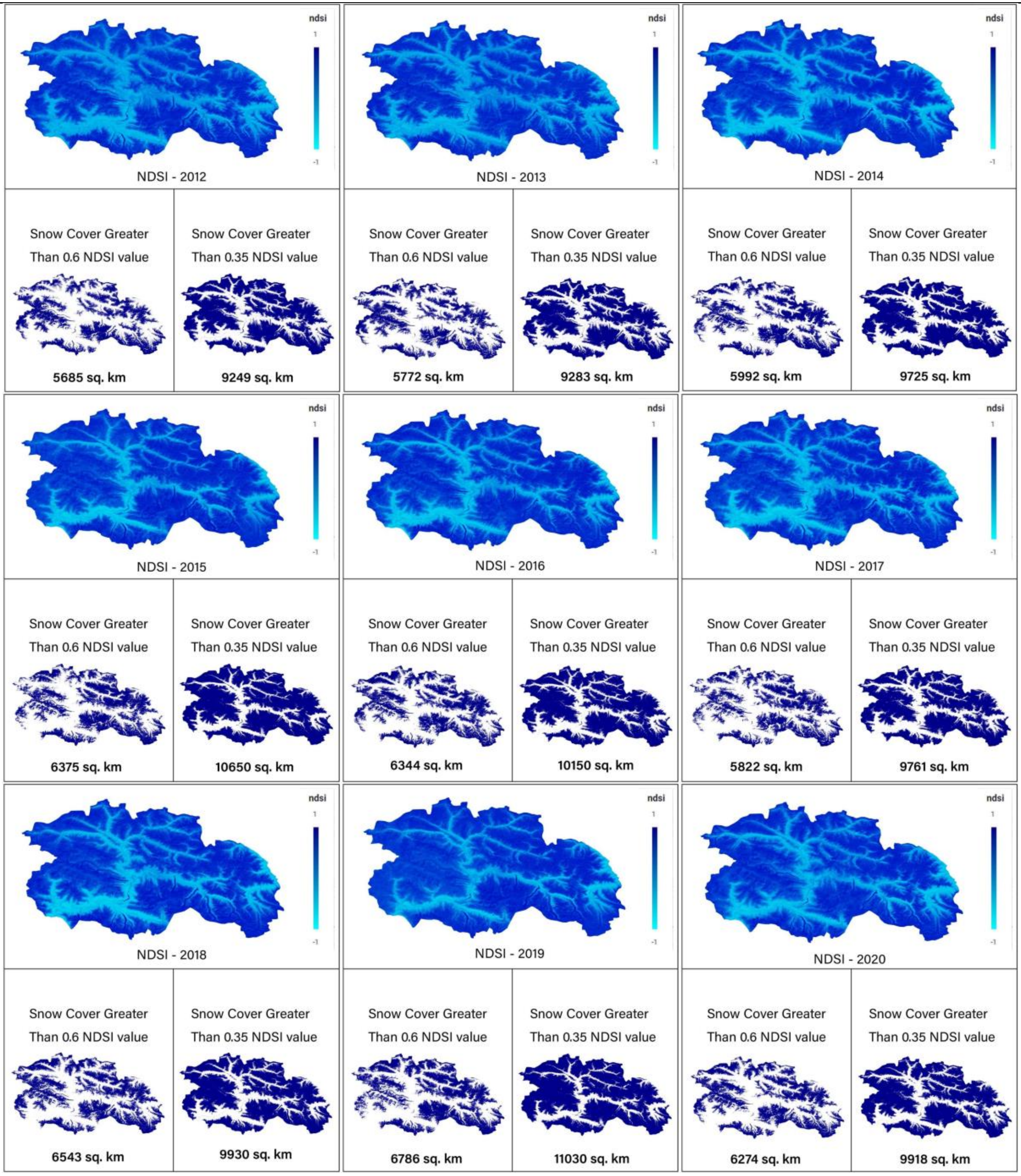


Figure 5: NDSI 1990-2020

Table 5: Details of Snow Cover Greater Than 0.6 NDSI value

Year	Snow Covered Area	(Total Area: 14312 sq.km)
1991	6679 sq. km	46.6% of total
1996	7357 sq. km	51.4% of total
2001	5915 sq. km	41.3% of total
2006	5799 sq. km	40.5% of total
2011	4941 sq. km	34.5% of total
2016	6344 sq. km	44.3% of total
2020	6274 sq. km	43.8% of total

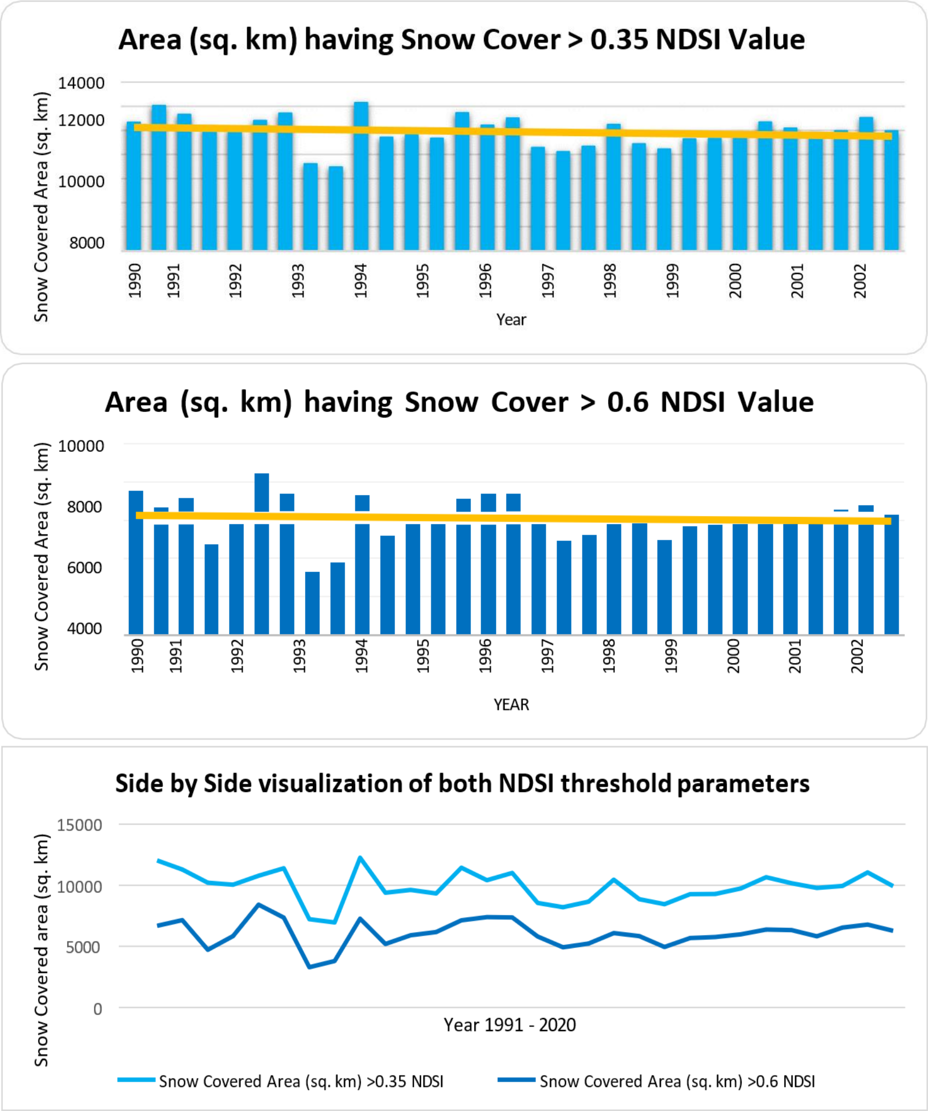


Figure 6: Graphical results, the trend in snow cover throughout the 30 years, from 1991 till 2020

The results reveal a relatively consistent pattern of annual snow accumulation and depletion over the 30-year period.

El Niño and La Niña:

Table 6: A timeline of all the [El Niño and La Niña] events/episodes from 1990 to present

El Niño				La Niña		
Weak	**Moderate**	**Strong**	**Very Strong**	**Weak**	**Moderate**	**Strong**
2004-05	1994-95	1991-92	1997-98	2000-01	1995-96	1998-99
2006-07	2002-03		2015-16	2005-06	2011-12	1999-00
2014-15	2009-10			2008-09	2020-21	2007-08
2018-19				2016-17		2010-11
				2017-18		

El Niño and La Niña are opposing phases of the El Niño-Southern Oscillation (ENSO) climate pattern, which has a significant impact on global weather and climate [17][18]. El Niño occurs when surface waters in the eastern tropical Pacific Ocean warm unusually, disrupting typical atmospheric circulation. This often leads to increased rainfall in the southern United States and Peru, while causing droughts in the western Pacific and Australia [19][20][21]. In contrast, La Niña is marked by cooler-than-average sea surface temperatures in the same region, leading to reversed weather patterns such as increased rainfall in Southeast Asia and Australia, and drier conditions in the southwestern United States and Peru [22]. Both El Niño and La Niña have far-reaching effects on ecosystems, agriculture, and economies worldwide. The detailed findings are provided in Table 6 and Figure 7.

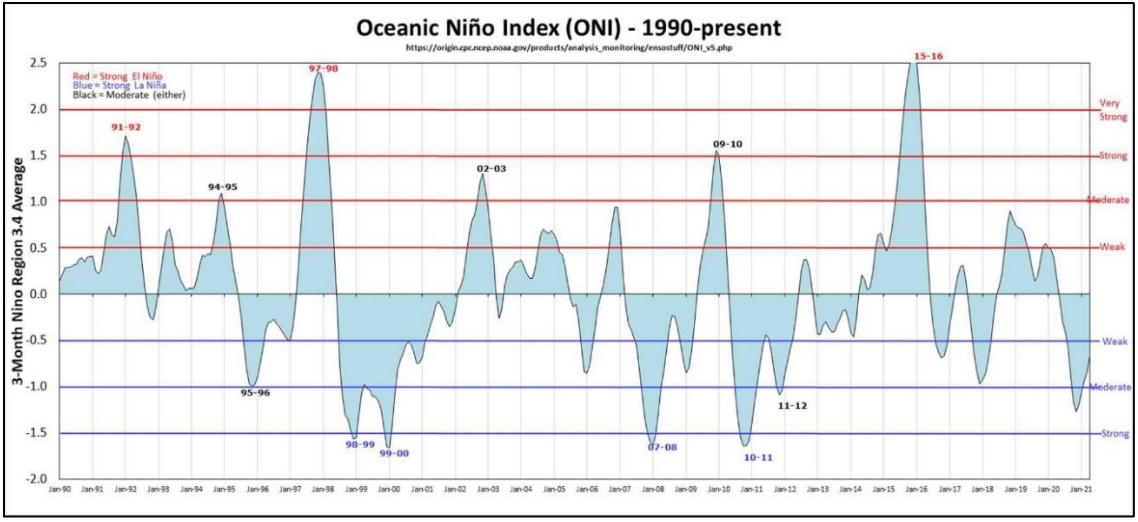


Figure 7: El Nino and La Nina events/episodes and intensity (1990-2020) Courtesy: Golden Gate Weather Services

It has been observed that the total snow-covered area significantly declines during strong El Niño events, but rebounds as El Niño conditions diminish and neutral or La Niña conditions prevail.

Discussion:

The results demonstrate a generally consistent pattern of annual snow accumulation and depletion throughout the 30-year study period. A notable decline in the total snow-covered area occurs during strong El Niño events, with recovery observed as El Niño conditions wane and neutral or La Niña conditions take over. The accelerated melting of glaciers and snow cover in Pakistan's Himalayan, Karakoram, and Hindukush (HKH) mountain ranges presents a critical threat to the country's water security, agricultural productivity, and energy generation. These glaciated regions, often referred to as the "Third Pole" due to their extensive ice cover, are undergoing significant changes driven by global warming and regional climate variability.

The study, utilizing Landsat 5, 7, and 8's Tier 1 Top of Atmosphere (TOA) reflectance products from 1991 to 2020, aimed to monitor the extent, mass, and distribution of snow cover in Hunza Nagar, Gilgit Baltistan. The findings revealed no major trends in total snow cover over the three-decade period but highlighted minor fluctuations, with significant dips during strong El Niño years. This suggests that while there are inter-annual variations, the overall snow cover in the region has remained relatively stable. The pronounced dips during El Niño years underscore the region's sensitivity to global climatic phenomena, aligning with other studies showing El Niño's influence on precipitation and temperature patterns globally, including South Asia [23][24].

The role of glaciated areas in cooling the planet and maintaining Earth's albedo is well-documented. The reduction in albedo due to melting snow and ice triggers a feedback loop that leads to further warming and accelerated melting [25]. This phenomenon poses a severe threat to regions like Pakistan, which depend heavily on meltwater for river flows, particularly the Indus River, crucial for agriculture, drinking water, and hydropower generation. The stability of these water resources is essential for the country's food security and energy needs.

The study highlights the importance of continuous monitoring and comprehensive regional assessments to understand the impacts of climate change on snow cover dynamics. Such efforts are vital for developing adaptive strategies to mitigate adverse effects on water resources, agriculture, and energy systems. Accurate predictions of meltwater availability can aid in planning irrigation schedules and managing water resources more efficiently, thereby supporting agricultural productivity and food security [26][27].

Additionally, understanding the relationship between global climatic phenomena like El Niño and local snow cover dynamics enhances the ability to forecast and prepare for variations in water availability. This is especially important for regions like Hunza Nagar, where communities rely on consistent meltwater flows for their livelihoods. The study’s use of Landsat data to quantify and visualize snow cover dynamics offers a robust methodology that can be applied to other glaciated regions facing similar challenges.

Limitations:

This study, while comprehensive in monitoring snow cover dynamics in Hunza Nagar, Gilgit Baltistan, from 1991 to 2020, has several limitations. The 30-meter resolution of Landsat data, though useful, may overlook finer-scale variations, and data accuracy could be affected by gaps from Landsat 7's Scan Line Corrector (SLC) failure after 2003. The study's focus on historical climate data and observed El Niño/La Niña events does not encompass all climatic interactions, and its findings may not be fully applicable to other HKH regions due to their distinct characteristics. Limited ground-based validation and the exclusion of local anthropogenic influences, such as land use changes and pollution, further constrain the study. Additionally, using annual median snow cover may mask seasonal variations, and reliance on specific remote sensing technologies and methodologies might introduce biases. These limitations underscore the need for ongoing improvements in data collection and analysis techniques for more comprehensive future research.

Conclusions:

The role of glaciated areas in maintaining climate stability highlights the significant threats posed by their accelerated melting. Continuous monitoring and comprehensive regional assessments are essential for developing effective adaptive strategies to mitigate the adverse effects on water resources, agriculture, and energy systems in Pakistan. Future research should aim to improve the accuracy of snow cover measurements and explore the impacts of other global climatic phenomena on regional snow dynamics to gain a deeper understanding of these complex interactions. Snow cover and its associated hydrological processes sustain intricate ecosystems and are vital for millions of people dependent on resources such as hydropower generation and irrigation. Given that snow cover is highly vulnerable to changing climate conditions and global warming, it is crucial to relate, monitor, and quantify snow cover dynamics in the context of climate change.

The results of this study indicate that while other areas of Gilgit Baltistan, such as Himalayan glaciers, have experienced a decline in snow cover, no significant decrease in total snow cover has been observed in Hunza Nagar, Pakistan. To enhance the understanding and management of snow cover dynamics in Pakistan's Himalayan, Karakoram, and Hindukush (HKH) mountain ranges, the study recommends expanding the use of advanced satellite technologies and ground-based observations for precise monitoring, integrating regional climate models and downscaling techniques to predict future impacts, and developing adaptive strategies for water resource management and agriculture. Engaging local communities and promoting educational initiatives are vital for garnering support for conservation efforts. Formulating integrated policies that address climate change, water management, and agricultural productivity, while encouraging international cooperation and data sharing, is essential. Further research, including long-term and interdisciplinary studies, is necessary to continuously monitor changes and refine predictive models, ensuring the resilience of water resources, agriculture, and energy systems in Pakistan.

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