A Review on: Impacts of Climate Change on Himalayan Glaciers and its Ecosystems

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ABSTRACT
The Himalayan Range is one of the world's most important and highest mountain ranges. It is found over various countries. The Himalayas were formed approximately 50 million years ago when the Eurasian plate collided with the Indian plate. This area is home to about 50 million people. The Himalayan areas are abundant in biodiversity and water resources. This research examines the changing climatic scenario of glaciers and their ecosystems as a result of atmospheric and anthropogenic activity. Species are becoming more vulnerable to extinction as a result of climate change. Climate change has previously had a devastating influence on Himalayan biodiversity ranges. Climate change will also have an impact on the lives and food security of the region's residents, who rely on the mountains' natural resources. According to the Intergovernmental Panel on Climate Change's fourth assessment report (IPCC, 2007), "the majority of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."

Keywords: *Cryosphere, permafrost, melting, glacier burst, GLOF (glacier lake outburst floods), glacier retreat*

INTRODUCTION

Glaciers are massive, thick masses of ice that form on land when snow falls and freezes. They've been there for years or centuries, and they're classified as a glacier. In layman's terms, a glacier is a vast body of ice and snow. "Blue ice" refers to glacier ice.

Glaciers are the colder areas of the earth that provide water to the Himalayan Rivers. Glaciers are responsible for storing 75% of the world's freshwater.

There are around 198,000 glaciers on the planet, covering an area of 726,000 km2, and if they all melted, sea levels would rise by approximately 405mm.

The Himalayas are home to 32,392 glaciers (Nepal, Bhutan, China, Afghanistan, and Pakistan). Apart from that there are 15,000 Himalayan glaciers present in India.

Mainly in India most glaciers lie in the territory of Ladakh and the state of Sikkim, Himachal Pradesh and Uttarakhand, few glaciers are also found in Arunachal Pradesh as shown in Figure 1.

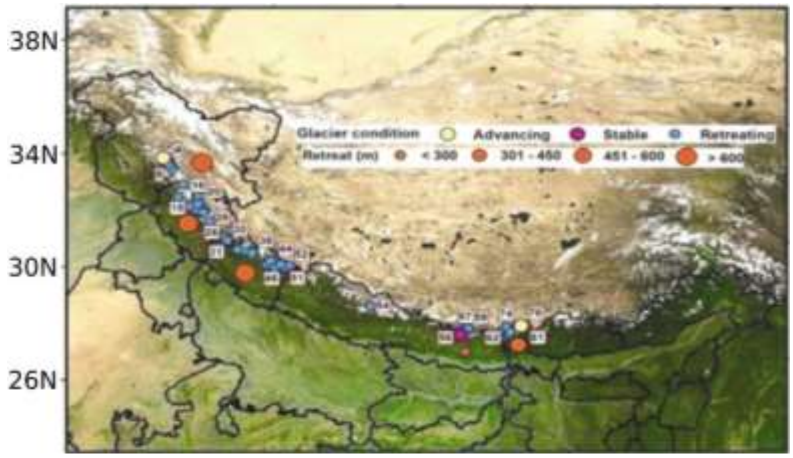

Fig. 1: *Range of Himalayan Glaciers in India.*
Source: https://www.semanticscholar.org/paper/Observed-Changes-in-Himalayan-Glaciers-Kulkarni-Karyakarte/edd581bbc80833132ae7ad3c8dc1133ef4da7985

Shekhar *et al.*, in (2017) observed that the youngest and highest Himalayan mountains sustain massive freshwater reserves in the form of snow, glaciers, natural lakes, permafrost, and wetlands while also supporting a population of 1.3 billion.[22]

Chevuturi *et al.*, in (2018) studied that the signs of climate Change Mountains from around the world are taken into account. The Himalayas are divided into five ranges: the Pir Panjal, Great Himalayas, Zanskar, Ladakh, and Karakorum.[6]

Sabin *et al.*, in (2020) studied that meltwater from the Himalayan glaciers feeds the region's rivers and streams, notably India's Indus, Ganges, and Brahmaputra River systems. These rivers offer roughly half of the country's total usable surface water resources.[21]

Dimri *et al.*, in (2021)[8] Snow cover has declined since the 1960s, with an enhanced decreasing trend during the 1990s and variable trends since 2000. Glaciers are losing mass and retreating at varying rates since the early 20th century, with an exception over the Karakoram region.

S. P. Singh & Thadani, in (2015) observed that the Himalaya range contains tremendous variation in elevation, precipitation, biodiversity, and human livelihood patterns. Unfortunately, our understanding of these ecosystems is still limited.[25]

Top 10 Notable Glaciers in India [Table 1]

Table 1: *List of Important Glaciers in India.*

Sr no.	Glaciers Name	Length	Location
1	Siachen Glacier	76 km	Ladakh
2	Gangotri Glacier	30 km	Uttarakhand
3	Barashigri Glacier	27.7 km	Himachal Pradesh
4	Zemu Glacier	26 km	Sikkim
5	Drang-Drung Glacier	23 km	Ladakh
6	Milam Glacier	16 km	Uttarakhand
7	Shafat Glacier/Parkachik Glacier	14 km	Ladakh
8	Machoi Glacier	9 km	Ladakh
9	Pindari Glacier	9 km	Uttarakhand
10	Chhota Shigri Glacier	9 km	Himachal Pradesh

HBRP PUBLICATION
Research and Reviews: Journal of Environmental Sciences
Volume 4 Issue 1

Siachen Glacier is the longest glacier in India, found in the Karakoram range in the Himalayas as shown in Figure 2. Gangotri Glacier, one of the major sources of the Ganges, is the smallest glacier in India as shown in Figure 3. Bara Shigri Glacier feeds the Chandra River, present in Lahaul and the Spiti Valley in Himachal. Zemu Glacier is the largest glacier in the Eastern Himalaya and is located at the base of Kanchenjunga, the 3rd-highest mountain in the world. Drang-Drung Glacier is also known as Drung Glacier and is located in the Kargil district of Ladakh. Milam Glacier, a major glacier of the Kumaon Himalaya, serves as a popular trekking destination. Shafat Glacier is also known as Parkachik Glacier. Pindari Glacier, found in the upper reaches of the Kumaon Himalayas, gives rise to the Pindar River. Chhota Shigri Glacier, present in the Western Himalayas, feeds the Chandra River. Machoi Glacier is the source of the Sind River and the Dras River, located in the northeastern Himalayan Range.

Fig. 2: *Siachen Glacier [Area: 2,500 km^2 (970 sq mi), Length: 76 km (47 mi).*
Source: https://www.dawn.com/news/1365369

Fig. 3: *Gangotri Glacier [Length: 30 km (19 mil), Area 2 to 4 km (1 to 2 mi)].*
Source: https://www.instagram.com/p/CeSzAAnPK5t/?utm_source=ig_web_copy_link

HIMALAYAN BIODIVERSITY

Pramanik & Bhaduri, in (2016) observed that the Indian Himalayan region (IHR) hosts over half of all blooming plants in India, with 30% being native to the region. The IHR is home to around 8000 angiosperm species, 44 gymnosperm species, 600 pteridophytes, 1737 bryophytes, 1159 lichen species, and 6900 fungi. The IHR contains approximately 816 recognised tree species, 675 of which are edible and roughly 1743 of which are medicinal.[18]

Flora of Himalayas [Figure 4-6]

Fig. 4: *Himalayan wild Rose.*
Source: http://indianflowersandherbs.blogspot.com/2010/06/himalayan-wild-rose.html

Fig. 5: *Himalayan Blue poppy.*
Source: https://www.yorkshireeflowereessences.com/products/himalayan-blue-poppy

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Fig. 6: *Sapria Himalyana.*
Source: https://www.britannica.com/place/Himalayas/Plant-life

Fauna of Himalayas [Figure 7-10]

Fig. 7: *Himalayan yak.*
Source: https://cdn.britannica.com/41/162641-050-4D61605C/yak-Himalayas-Nepal.jpg

Fig. 8: *Himalayan Musk Deer.*
Source: https://geographynature.com/en/5982-musk-deer-the-smell-of-an-angel-a-demon-fangs/

Fig. 9: *Snow leopard.*
Source: https://www.nationalgeographic.com/animals/mammals/facts/snow-leopard

Fig. 10: *Red Panda.*
Source: https://www.worldwildlife.org/species/red-panda

CLIMATE CHANGE OVER CRYOSPHERE

Dimri *et al.*, in (2021) studied that Mountains cover around 25% of the earth's surface. The mountain range is home to over 125 percent of the world's population. Connected rivers nourished by snow and ice melt play an important role in the life-support system. Mountain systems are extremely vulnerable to climate variability and change.[8]

Adler *et al.*, in (2019) observed that in recent years, the effects of climate change on the high alpine cryosphere and downstream regions have become a major focus of study efforts. Parallel to this, the Intergovernmental Panel on Climate

Change (IPCC) has presented an opportunity in its sixth assessment cycle (AR6) to address and respond to information gaps on climate change consequences in the high mountain cryosphere, further driving research engagement on the topic.[1]

Azam *et al.*, in (2018) observed that according to the glaciological mass budget, the Himalayan was similar to the global average until 2000, and is likely less negative after that date. The Himalaya's mass waste resulted in increased debris cover, the formation of glacial lakes, and potentially decreased ice velocities.[4]

Parry *et al.*, in (2020) Studied that HKM (Hindukush Mountain) glaciers produce 40% of the world's population water. These glaciers have lost mass during the last century and will continue to lose bulk in the future. The precise ways in which glaciers will respond to future climate change are unknown; many will melt completely, but some will transition to debris-covered glaciers, which will slow melting, and others will transition to rock glaciers, the response to which to atmospheric warming and changes in precipitation is unknown.[17]

The current state of knowledge on the IHR, focusing on climate (i.e., temperature and precipitation)

Temperature

S. Singh *et al.*, in (2016) observed that because of its ability to represent energy exchange over the earth's surface, changes in air temperature are regarded as a good indicator of global climate change. Global meteorological data reveal a systematic rise of 0.85 degrees Celsius from 1885 to 2012, following a decadal rise of 0.05 degrees Celsius in global mean temperature. Yet, the warming trend has not been consistent over the world. According to studies based on instrumental data, the Himalayan ranges have undergone a warming trend that is more than twice as fast as the global average. The cause of this anomalous local climatic warming has been attributed to anthropogenic greenhouse gas emissions as well as deforestation, both of which have been proposed as dominant climate forcing agents. [23]

Precipitation

Mir *et al.*, in (2021) studied that Climate change has had a significant impact on precipitation across the Himalayas. Precipitation does not demonstrate a continuous pattern over a longer time period, and there are irregularities at both the spatial and seasonal levels. This could be explained by the effect of local thermodynamic and orographic processes.[12]

Bhutiyani *et al.* in (2010) observed that a significant declining trend in monsoon and average annual rainfall was observed in the northwest Indian Himalaya region from 1866 to 2006, and a similar trend was observed in the western Indian Himalaya region from 1960 to 2006. A general trend of decreasing precipitation was seen in most locations, particularly in Jammu & Kashmir and Uttarakhand. Precipitation is generally decreasing in the western Himalayas, with the exception of Jammu and Kashmir, where monsoon and annual precipitation are increasing. Winter precipitation is also decreasing in the western Indian Himalaya.

IMPACTS OF CLIMATE CHANGE ON HIMALAYAN REGIONS

Glacier Melting

Keesari, in (2021) observed that glaciers are an essential component of the Earth's natural system. It is one of the most trustworthy and sensitive indicators of climate change. It is predicted that over

10,000 glaciers in the Indian Himalayas are receding at a rate of 100 to 200 feet every decade. Moreover, melting has been twice as fast since the year 2000 as it was 25 years ago, owing to human-caused climate change. It is also predicted that if greenhouse gas emissions continue at their current rate, two-thirds of Himalayan glaciers will vanish by the end of the century.[10]

Maikhuri *et al.*, in (2018) studied that glacier mass balance analyses show that all mountain glaciers contributed 0.2 to 0.4 mm/yr to rising sea level during the last century. Global mean temperature has risen by just over 0.60 C over the last century, with recent warming accelerating. The most significant impact will be on the world's water supply. Several climatologists believe that the disappearance of Himalayan glaciers is one of the first visible symptoms of man-made global warming as shown in Figure 11.[11]

Fig. 11: *Melting of glacier ice.*
Source: https://www.newindianexpress.com/nation/2020/mar/03/forest-fires-stubble-burning-influencing-melting-of-gangotri-glacier-2111304.html

Ganjoo, in (2021) studied that one issue that has yet to be resolved is the melting of glaciers in the Himalaya. The IPCC's (Intergovernmental Panel on Climate Change) assessment report IV of 2007 estimated that the glaciers in the Himalaya will vanish by AD 2035, which was rejected by a substantial section of glaciologists in India. The irregular behaviour of glaciers across the Himalayas was documented in a study issued by the Government of India's Ministry of Environment and Forests.[9]

The glaciers in the Karakorum Mountains are less affected by climate change because of the following factors:
(a) The strengthening and shifting of Westerlies to lower elevations transports more precipitation to this portion of the Himalaya.
(b) Winter precipitation has grown over the twentieth century.
(c) Summer temperatures have decreased slightly in the second half of the twentieth century.

Impact on Food

G. C. S. Negi & Mukherjee, in (2020) observed that agriculture is the primary source of income for mountain inhabitants in the western Himalayan region. Mountain agriculture is primarily rain-fed and reliant on biomass energy from the surrounding forests. In Uttarakhand, for example, over 40 different crops and hundreds of cultivars of cereals, millets, pseudo-cereals, pulses, and tuber crops are grown. Another excellent illustration of the region's tremendous agri-diversity is mixed farming of 12 crops (Baranaja). These crops have adapted to local environmental conditions and can survive environmental dangers and other natural hazards, contributing to the food and nutritional security of hill farmers for many generations. [13,14]

Unfortunately, the area cultivated with traditional crops has declined dramatically (>60%) in recent decades, and several crop species, such as Panicum miliaceum, Glysine spp., Setaria italica, Hibiscus sabdarffia, Vigna spp., and Perilla frutescens, are on the verge of extinction.
The irrigation systems (known locally as guls) have been seriously damaged as rainfall has become unpredictable and springs have dried up. Similarly, a comparison of temperature data suggests that climate change has a negative impact on fruit harvests, as recorded in the Kullu valley (Himachal Pradesh).

Negi *et al.*, in (2012) studied that some of the documented impacts on mountain food production systems linked with CC in the Himalayan region are :

- Decreased irrigation water availability;
- Severe drought events and fluctuations in the rainfall regime, resulting in crop germination and fruit set failure;
- Weed invasion in croplands (e.g., Lantana, Parthenium, Eupatorium);
- an increase in the frequency of insect-pest assaults; and
- a decrease in crop output.

These causes have resulted in a loss of agri-diversity and changes in crops and cropping patterns in the Western Himalayan region, resulting in crop field abandonment and population out-migration.

Impact on Biodiversity

Dahal *et al.*, in (2021) observed that Climate change threatens one of six species. Yet, the effects of climate change on Himalayan biodiversity have not been thoroughly investigated. Biodiversity is the consequence of more than 3.5 billion years of evolution on Earth. The Himalayan highlands are known for having the most glaciated areas outside of the polar regions, and glaciers progressed several kilometres during the LGM (Last glacial maximum). The Himalayas are undeniably a climatically unstable mountain range with great biodiversity.[7]

Impact on Ecosystem

Palomo, in (2017) observed that climate change has an impact on ecosystem services and people's well-being in high alpine environments. Specifically, it has an impact on food and feed supply, water availability, natural disaster regulation, spirituality and cultural identity, aesthetics, and recreation. Permafrost melting, glacial lake outburst floods (GLOFs), and extreme weather events are the primary causes of hazards.[15]

CLIMATE CHANGE DUE TO ANTHROPOGENIC ACTIVITIES

Chakraborty *et al.*, in (2018) reviewed that The Himalayan forests are vulnerable to the effects of climate change and are suffering from severe ecological decline as a result of anthropogenic pressures.[5]

Romshoo *et al.*, in (2022) observed that the concentration of greenhouse gases (GHGs), black carbon, and other pollutants from motor traffic near glaciers has significantly increased the GHGs (Greenhouse gases).[20]

Black Carbon Pollutants
P. S. Negi & Pandey, in (2021) studied that the presence of black carbon (BC) aerosols in the ambient air of Himalayan glaciers is thought to be one of the major causes to Himalayan regional environmental disturbance.[14]

Atmospheric BC are carbonaceous aerosols that absorb solar radiation and are co-emitted with several other gaseous pollutants after the incomplete combustion of biomass and fossil fuels. The greater concentrations of BC aerosols documented in Himalayan glacier valleys have piqued the scientific community's interest in recent decades. Higher levels of BC aerosols in the Himalayan region's ambient air are thought to be one of the main causes worsening the environment of the Himalayan cryosphere and glacier valley.

These aerosols have the ability to disrupt the normal radiative balance of the atmosphere and are thought to be the second most important cause of global warming after carbon dioxide (CO2). According to studies, these light-absorbing aerosols have the potential to disrupt the pattern of the Indian summer monsoon, resulting in accelerated melting of glaciers; increasing BC pollutants in the Himalayan region is bound to increase atmosphere temperature, causing a change in radioactive energy balance, which is likely to affect the glacier-snow regime, ecosystem services, livelihood system, as well as the sustainability of local and regional flora, fauna, and ecosystems.

Hydro Geochemical Characteristics
V. B. Singh & Kumar, in (2022) observed that the hydro geochemistry of glacial melt water reveals vital information regarding solute acquisition processes, chemical weathering and CO2 consumption, atmospheric and anthropogenic activities, solute dynamics, and the impact of climate on melt water chemistry in the glacier environment.[26] The hydro geochemistry of melt water pouring from roughly 25 glaciers spread over the Himalaya. Except for the Batal, Dokriani, Chaturangi, Dudu, Bagni, Raktvarn, and Gangotri glaciers, where SO42 is found to be the main anion, indicating a likely preponderance of sulphuric acid-mediated weathering in these glaciers.

Carbonate weathering has been identified as the primary solute acquisition process governing the hydrogeochemistry of melt water from Himalayan glaciers. The main ion concentration in glacier melt water in the Garhwal and Himachal Himalayan areas is generally low during peak flow or monsoon season and high during late melt or post-monsoon season. The chemical weathering rates of Chhota Shigri glacier are lower than those of Dokriani glacier, which may be attributable to the presence of large supraglacial moraines and significant rainfall during the monsoon season in the Dokriani glacier basin.

Glacier Burst
A glacier burst, in essence, is a cascading risk, with cascades of glacier bursts, cloudbursts, severe rain, and subsequent landslides. It occurs as a result of increased water, pressure, or structural instability.

Nadim *et al.* in (2006) observed that Flood and landslide disasters are widespread in northern India's Himalayan states due to the unfavourable interplay of climate, lithology, geography, and seismicity.

GLOF (Glacier Lake Outburst Floods)
Ahmed *et al.*, in (2021) studied that Climate change is having a significant impact on the Himalayas. Regional warming in the Himalayas has been shown

to range between 0.15 to 0.60°C every decade, which is faster than the global average of 0.74°C per 100 years. As a result of this warming trend, visible glaciological changes in the Himalayas have occurred, resulting in the formation, expansion, and extinction of numerous types of glacial lakes. These toxic lakes endanger the downstream community and infrastructure. By a meta-analysis of peer-reviewed scholarly literature from 2001 to 2020, this study attempted to critically examine the advancement in Glacier Lake Outburst Floods (GLOF) research and comprehend its dynamic from many perspectives.[2]

Talukder *et al.*, in (2021) observed that several disasters in the IHR have emphasised the fragility of the region's population, most notably the devastating June 2013 events in Uttarakhand.[27]

Kedarnath disaster

Allen *et al.*, in (2016) reviewed that sever rains in June 2013 generated many mass movements across Uttarakhand, including two huge debris flows on June 16 and 17, which damaged the village of Kedarnath as well as the towns of Rambara and Gaurikund further downstream. Throughout the region, flash flooding and landslides killed over 6000 people, the great majority of them were linked to the Kedarnath disaster as shown in Figure 12. Many roads and bridges were destroyed or substantially damaged, and at least 30 hydropower plants were destroyed or severely damaged. Some 100,000 pilgrims and tourists were stuck due to the devastation of roads and trekking routes until military and civic officials could complete rescue efforts.[3]

Fig. 12: *Kedarnath disaster (glacier burst).*
Source: https://timesofindia.indiatimes.com/city/dehradun/chorabari-lake-responsible-for-2013-kedar-disaster-swelling-up-again/articleshow/69864212.cms

Extraordinary early monsoon rains between June 15 and 17, 2013, combined with melting snow, created massive floods in Uttarakhand's rivers, including the Bhagirathi, Alaknanda, Mandakini, Dhauliganga, and Kali, resulting in major mud- and landslides. Hundreds of pilgrims were stranded at several pilgrimage sites and on the final path. Severe rains triggered widespread landslides and flash floods in the Mandakini valley, causing irreparable damage to life and property, including the full destruction of 60% of the 14-kilometer pedestrian route from Gaurikund to Shri Kedarnath town. This flash flood catastrophe altered the topography of Uttarakhand, making the entire region more unstable and vulnerable. The calamity, which has resulted in around 5,000 deaths and the disappearance of nearly 1 lakh people, serves as a wake-up call to cease environmental damage.

Tariyal, in (2017) reviewed that the flash flood and landslides caused significant damage to infrastructure, agricultural areas, human and animal life, roadways, and natural resources. A calamity of this size has probably not occurred in the region in the last 100 years. As a result, this calamity qualifies as an Extreme Climatic Event of the Century. Snowbound places like as Badrinath, Kedarnath, Gangotri, Yamunotri, and Hemkund Shahib were severely impacted by nature's wrath. The historic Shri Kedarnath shrine was one of the worst hit areas, with the most damage and casualties reported. [28]

Chamoli disaster [Figure 13]

Pandey *et al.*, in (2021) studied that the recent disastrous flood that occurred on February 7, 2021 in the catchment of the Rishiganga and Dhauliganga valleys in the Chamoli district of Uttarakhand, an Indian Himalayan state.[16] On February 7, 2021, the catchments of the Rishiganga and Dhauliganga valleys in Uttarakhand's Chamoli district were devastated by a devastating flood caused by a large rockslide caused by wedge failure.

It is estimated that a massive rockslide containing base rock, deposited ice, and snow detached from the northern slopes of the Trishul mountain range near Ronti Glacier and created a vertical fall of nearly 1700 m before severely impacting the Ronti Gad valley located 1.5 km downstream of the Ronti Glacier snout.

The gigantic detached mass of rock and ice immediately flowed downstream through the glaciated valley, entraining snow, debris, and mud along the way, causing fast fluidization, massive water waves, and partially or totally washing away the hydropower projects and bridges in its path.

Fig. 13: *Chamoli disaster (glacier burst).*
Source: https://www.dw.com/en/india-dozens-feared-dead-as-himalayan-glacier-crashes-into-dam/a-56484553

Glacier retreat

S. Singh *et al.*, in (2018) studied that Glaciers are the planet's coolants and the lifeblood of many of the world's major rivers.[24] They hold over 75% of the world's fresh water and serve as a source of major rivers. The connection of glaciers and climate is a particularly delicate technique. On a worldwide basis, air temperature is thought to be the most critical element in determining glacier retreat, however this has yet to be proven for tropical glaciers.

Rashid & Majeed, in (2020) studied that Changes in the snout, area, and mass of Sikkim Himalaya's largest glacier, Zemu, were studied using 87 years of earth observation data from 1931 to 2018.[19]

The GlabTop model was used to forecast glacier thickness and potential lakes in the future. The study is significant because huge hydropower infrastructure is being built without any understanding of the region's receding glaciers. The glacier receded 30.67% between 1931 and 2018, at a rate of 0.35% each year. Between 1931 and 2018, the glacier's snout retreated about 797 m at a rate of 9.1 m a1. From 2014 and 2018, the rate of retreat climbed to 20 m a1. According to geodetic mass balance estimations, the glacier lost 6.78 Gt of mass at a rate of 84.8 Mt a1 between 1931 and 2012. Between 2000 and 2012, mass loss accelerated at a pace of 276.5 Mt a1.[29,30]

CONCLUSION

- Glaciers are the important part of our ecosystem. It mainly found in the ranges of Himalayas surrounded with highly flora and fauna. It covers most of biodiversity over the regions. Atmospheric and also Anthropogenic activities disturb the climate of Himalayan Ranges. Due to these Activities shows an adverse impact on glaciers like melting, outburst, floods, retreat and also shows impacts on fauna and flora, food resources and shows impacts on humans.
- It can be challenging to dispose of carbon dioxide from the energy cycle in developing countries. Yet it's now simpler to cut back on emissions of black carbon. This can be accomplished by improving the diesel filters in automobiles, minimising deforestation, and switching to solar energy or natural gas for stoves that burn biomass. Although these modifications may be expensive, the decarbonization process is much more expensive. By slowing global warming and reducing black carbon emissions, it helps to avoid glacial melting.
- Planting trees can reduce atmospheric carbon dioxide, which helps in the fight against global warming. The creation of new forests can aid in reducing carbon dioxide levels by allowing plants to absorb CO2 and produce oxygen through a process known as photosynthesis. Landfills emit CO2 into the atmosphere. Papers disposed of in landfills eventually decompose, releasing carbon dioxide into the environment. Recycling, however, helps to lessen these emissions and instead lessens global warming and glacial melting (by keeping rubbish out of landfills).
- There are several risks that could arise from the rapid melting of glaciers in the next years if we do not act to mitigate this threat promptly. And each of us has a role to play in contributing in the reduction of these harmful emissions, resulting in a realistic reduction in future global warming. Whilst it may be impossible to completely stop glacial melting, we may take the necessary steps to reduce the rate of melting for the sake of our environment.

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