DOI: 10.52131/pjhss.2023.1103.0699

Pakistan Journal of Humanities and Social Sciences

Volume 11, Number 03, 2023, Pages 3810–3822
Journal Homepage:
https://journals.internationalrasd.org/index.php/pjhss

Global warming and Ice Nucleation in Central Himalayas: A Case Study of Skardu District

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ARTICLE INFO

Article History:
Received: July 10, 2023
Revised: September 28, 2023
Accepted: September 29, 2023
Available Online: September 30, 2023

Keywords:
IN (Ice Nucleation)
ICM (Ice Melt Water)
CCN (Cloud Condensation Nuclei)
Plant-1Cedrus Deodara (Roxb.Ex D. Don) (Common Name Diar)
Plant 2 Which Is Pinus Roxburghii Sargent (Botanical Name Chir)

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

Water is an essential need for life and demand for water supply is exponentially increasing with elevating human population. Ice nucleation plays a fundamental role in shaping precipitation patterns and influencing the Earth's climate system. Skardu's unique location amidst the Karakorum. As temperatures decrease, there is a noticeable increase in stream water and ice melt water, potentially impacting biological activity and ecological processes. Following Vali's equation and finding number of frozen drops from -1 to -10 degree Celsius after 5 mints incubation at each degree. The correlation between temperature and frozen drops adds complexity, highlighting the heightened sensitivity of environmental phenomena to temperature variations, with frozen drops peaking at extremely low temperatures. Ice nucleation results at Skardu showed that stream water can maximize IN 17.5 times from its starting point of freezing points while ice melt water increased 9 times, sediments 5 times. Biotic factors of plant 1 and plant 2 showed 25 times and 24 times increase in IN from starting point of freezing. Result of IN at Shigari showed, stream water increased 9.5 times, ICM increased 9 times, sediment 4 times, plant 21 times and plant 2 showed 23.5 times from their first freezing happened. Cold desert, IN results showed that stream water increased 11 times, ICM 19 times, sediments 4 times, plant-1 25 times and plant-2 24.5 times increased in IN from their first freezing point.

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1. Introduction

An ice nucleation (IN) stands as a microscopic entity, an aerosol particle wielding the ability to set in motion the intricate dance of ice crystal formation within clouds through four foundational mechanisms: deposition, condensation-freezing, contact-freezing, and immersion-freezing (Vali, 1985). The ramifications of IN transcend the boundaries of the ethereal cloud realm, reaching into the very fabric of precipitation and climate dynamics. IN assumes a pivotal role in orchestrating transformations in water's phase within cold clouds, leaving an indelible mark on precipitation through the well-studied Bergeron process (Bergeron, 1935). Furthermore, the influence of IN ripples through the microphysical and radiative properties of clouds, thereby contributing to the nuanced modulation of the Earth's climate system (Bakhtyar, Kacemi, & Nawaz, 2017; S. Li, Huang, & Hu, 2003; Liu, Penner, Ghan, & Wang, 2007). As we unravel the secrets of atmospheric processes, a deep dive into understanding the activation processes of IN becomes not only a scientific pursuit but a vital necessity for short-range precipitation forecasting and climate change prediction. The past five decades have witnessed a plethora of studies scrutinizing the multifaceted effects of IN on precipitation and climate, dissecting aspects such as nucleation efficiency and ice nucleation rates (Beard, 1992; Hendricks, Kärcher, & Lohmann, 2011; Isono & Komabayasi, 1954; Kanji et al., 2019; Mohsin, Kamran, Nawaz, Hussain, & Dahri, 2021; SATO, KIKUCHI, ASUMA, UYEDA, & KAJIKAWA, 1998). Recent strides in scientific modeling, particularly cloud-resolving models, have hinted at the profound impact of IN on the orchestration of cloud ensembles and radiation, intricately weaving into the broader tapestry of global warming (Ekman, Engström, & Wang, 2007; Phillips, Donner, & Garner, 2007; Shittu, Hassan, & Nawaz, 2018; Yin, Wang, & Zhai, 2012; Zeng et al., 2008; Zeng et al., 2009).

Yet, the enigmatic role of IN in the development of clouds and precipitation remains a captivating puzzle, beckoning further exploration and inquiry (Prenni et al., 2007). The challenge lies not only in the subtle nuances of each IN, with their distinct nucleation efficiencies and ice nucleation rates Rogers (1988), but also in deciphering the intricate interplay of IN within the dynamic context of clouds and precipitation. Against the backdrop of a rapidly changing world, marked by escalating aerosol emissions due to desertification and industrialization, regions like China stand as crucibles for investigating the profound impacts of IN on precipitation and climate (Z. Li et al., 2007). Pioneering studies, such as those conducted by C. Zhao, Tie, and Lin (2006) and Choi, Lindzen, Ho, and Kim (2010), have delved into the symbiotic relationship between aerosol concentration and precipitation, revealing a positive feedback loop where increased aerosols lead to reduced precipitation, subsequently fostering higher aerosol concentrations. Additionally, the research conducted by Zhai, Zhang, Wan, and Pan (2005) aligns with the intriguing hypothesis that heightened IN concentrations may yield less frequent but more intense precipitation events. Nevertheless, the task of quantifying the intricate relationships among IN, cloud condensation nuclei (CCN), and other atmospheric factors presents a formidable challenge. To unravel the connection between IN concentrations, global warming, and precipitation, a wealth of comprehensive IN measurement data is indispensable. In essence, the exploration of IN's multifaceted role not only enriches our understanding of atmospheric processes but also underscores the profound implications of these intricate interactions on both regional and global climatic patterns. Studies by (Akila, Priyamvada, Ravikrishna, & Gunthe, 2018; Hock et al., 2017; Joyce et al., 2019; Kanji et al., 2019; Knopf, Alpert, & Wang, 2018; C. Li, Liu, Goonetilleke, & Huang, 2021; S. Li et al., 2003; Masson-Delmotte et al., 2021; Nawaz et al., 2021; Sanchez-Marroquin et al., 2020; Šantl-Temkiv et al., 2019; B. Zhao et al., 2019) and Jaganathan, Dalrymple, and Pritchard (2020) provide insights into potential strategies Ice Nucleation and Global Warming.

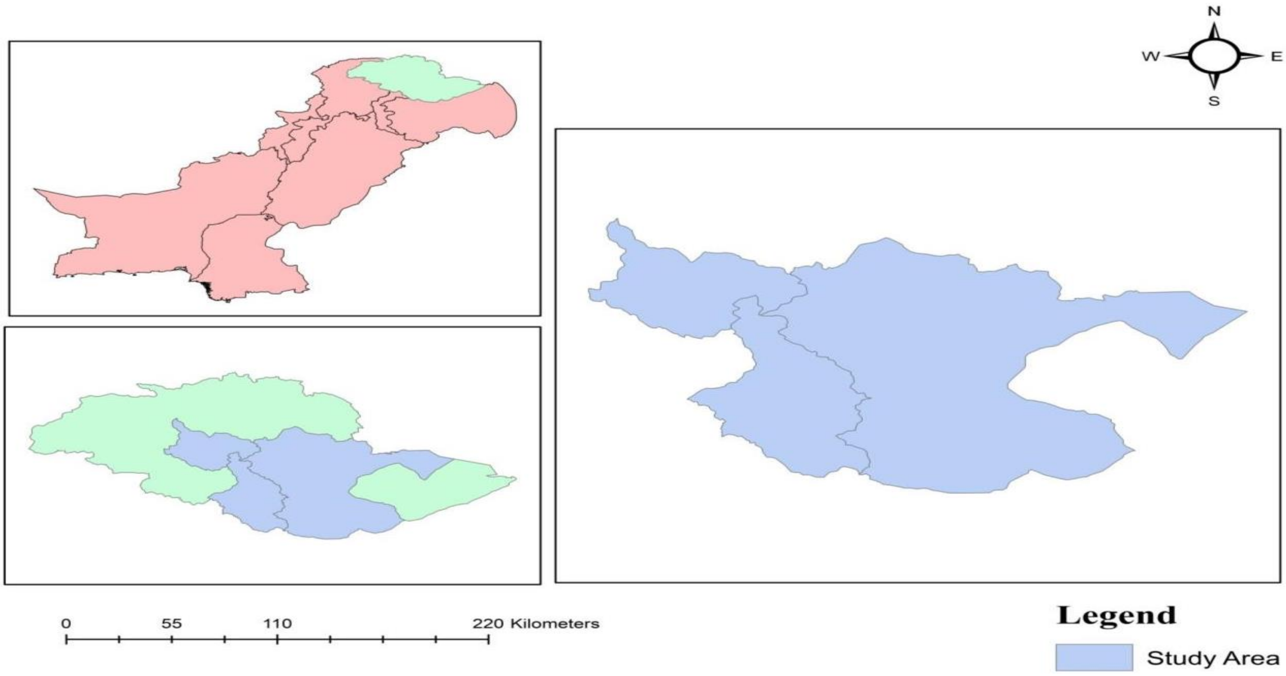
This study utilized the NDSI and temperature data to assess the frozen point relation in the study area. The objective of the study was to find the relation between the Ice Nucleation and temperature how they can promote the global warming in region and how the global warming impact the glacier malting process. Global warming and potential impacts on ice nucleation in Himalaya's mountains. It is significant to identify the degree of ice nucleation to understand water cycle to meet needs of water demand for agriculture, industries, and domestic utility. What are the dynamics of ice nucleation under variability of temperature aligned with biotic and abiotic factors and these can be evaluated for policy making for sustainability? The study area is contributory of river Indus which provides water for irrigation that is why it has grave significance to understand parameters for preventive measures.

2. Material and Methodology

2.1. Study Area

The most beautiful region of the central Himalayas is Skardu (35°16'44" N 75°36'48" E, altitude is 2225m). Skardu encompasses the captivating and geographically diverse Skardu district, a region nestled within the breathtaking landscapes of Gilgit-Baltistan, Pakistan (Z. Hussain et al., 2019). Skardu is a pivotal district within the Karakoram Range, known for its extraordinary topography, rich cultural heritage, and strategic importance. Here, the mighty Indus River snakes its way through dramatic valleys, surrounded by towering mountain peaks, including some of the world's highest, such as K2 (Akbar, Ahmed, Hussain, Zafar, & Khan, 2011). Skardu district spans an extensive area, characterized by a varied terrain that includes expansive valleys, rugged mountain ranges, glaciers, and pristine lakes. The district serves as the gateway to some of the most iconic mountain ranges, including the Karakoram, Himalayas, and the Hindu Kush, making it a hub for trekking, mountaineering, and adventure tourism. The district headquarters, Skardu Town, is a cultural and economic center surrounded by ancient monasteries, historic forts, and traditional villages that reflect the unique blend of Balti and Tibetan cultures. Skardu's cultural richness is further emphasized by its festivals, music, and distinctive handicrafts (Muhammad et al., 2010). The climate in Skardu is characterized by cold winters, with temperatures often dropping below freezing, and cool summers, providing a unique setting for the study of climatic patterns and their impact on the region's environment. This study area presents an opportunity for comprehensive research across various disciplines, including geology, climatology, anthropology, and environmental science (A. Hussain et al., 2010). Whether exploring the ecological significance of the Deosai National Park, understanding the dynamics of glacial systems, or delving into the socio-economic fabric of the local communities, Skardu district stands as a compelling and multifaceted region for academic inquiry and exploration. For sample collection Skardu, Shigari and cold desert were selected to have uniform assessment of the study area.

Figure 1: The Study Area



2.2. Data Source

The Landsat 8 satellite imagery for the year 2014 were acquired from the United States Geological Survey website, providing a comprehensive visual snapshot of the study area. Simultaneously, temperature data spanning the years 2002 to 2022 were obtained from the official website of the Pakistan Meteorological Department, offering a detailed temporal perspective on the climatic conditions within the region. To enrich our understanding of ice nucleation, samples were meticulously collected in a random fashion from various locations within the study area. This sampling approach ensures a representative selection, capturing the diverse environmental conditions that contribute to the intricate dynamics of ice nucleation. Each sample serves as a microcosm, encapsulating the nuanced interplay of factors influencing this phenomenon, including temperature variations, topography, and atmospheric conditions. This multi-sourced data, combining high-resolution satellite imagery and long-term temperature records, along with the randomly collected ice nucleation samples, forms the foundation of our comprehensive analysis. By synergizing these diverse datasets, we aim to unravel the intricate relationships between environmental variables and ice nucleation processes, shedding light on the climatic nuances of the study area.

2.3. Data Analysis

2.3.1. Normalized Difference Snow Index (NDSI)

Utilizing the Normalized Difference Snow Index (NDSI), we conducted a comprehensive analysis to quantify the extent of snow cover in the Skardu District. The NDSI calculations were based on the spectral information derived from the green and Shortwave Infrared

(SWIR) bands of Landsat 8 imagery (Poussin, Timoner, Chatenoux, Giuliani, & Peduzzi, 2023). Specifically, Band 3 was employed to represent the green band, while Band 6 represented the SWIR band within the Landsat 8 dataset (Kholdorov et al., 2023). The NDSI was computed using the formula:

$$NDSI = (Green\ band + SWIR\ band) / (Green\ band - SWIR\ band) \quad (1)$$

This index serves as a valuable tool for monitoring ice nucleation across diverse areas within the region. Our choice of NDSI was deliberate, as it has demonstrated superior efficacy compared to other spectral bands (Chen & Zhu, 2022). By leveraging this specific index, we aim to enhance the precision and sensitivity of our analysis, providing a more accurate depiction of ice nucleation patterns in various geographical locations. '’

2.3.2. The Vali method of nucleating ice

A sterile aluminum sheet was used, and 50 drops of 25 microliters containing a dilution suspension of 5 x 10 ^{6} to 5 x 10^{8} cells/mL were spread out and floated on a cooling bath in accordance with the Vali method. The temperature was first set at -1°C and then decreased by 1°C to -10°C. Each 1°C temperature adjustment was incubated for 5 minutes before the frozen drops were visually counted. The calculation of ice nucleation per bacterial cell was done using the method suggested by Vali (2019) and equation 2.

$$c(T) = ln\,(No) - ln\,(No - N(T)) \quad (2)$$

A in this case denotes the concentration of bacteria per drop, no denotes the number of drops tested, N the total number of frozen drops at temperature T, and c(T) the number of ice nuclei per bacterial cell at that temperature (Vali, 2019). For instance, the maximum temperature at freezing was reached when computing the degree of INA with an infinite number of ice nuclei per cells. Vali’s equation doesn’t address impact of altitude with degree ice nucleation and other variables. It doesn’t connect biotic and abiotic parameters to classify their impact on ice nucleation. In order to assess impact of temperature and freezing Vali’s approach was modified. The samples were taken from three abiotic factors sediments, ice melt water and stream water to test relationship with temperature to find number of frozen drops. Two biotic factors were considered named plant-1 [(Plant-1Cedrus deodara (Roxb.ex D. Don) (common name Diar)] and plant-2. [Plant 2 which is Pinus roxburghii Sargent (botanical name Chir). Temperature was varied from -1 to -10-degree calcius while incubating samples for five minutes after putting on aluminum foil floor of an incubator.

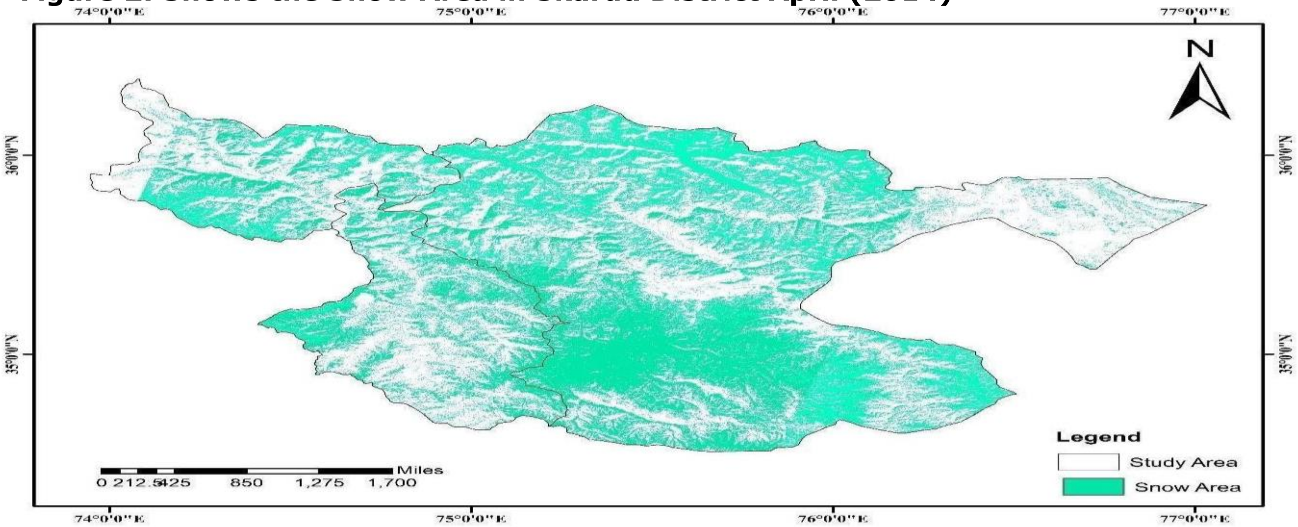
3. Results and Discussion

The study of ice nucleation dynamics in the context of global warming holds particular significance in regions with unique climatic conditions, and the Central Himalayas, specifically the Skardu District, emerges as an intriguing case study. Situated at the intersection of the Karakoram, Himalayas, and Hindu Kush Mountain ranges, Skardu serves as a critical location to understand the intricate interplay between ice nucleation processes and the broader implications for global climate change. Skardu, being a high-altitude region, experiences distinctive climatic conditions. The study delves into the specific dynamics of ice nucleation in response to the region's unique topography, which includes towering peaks, glacial formations, and the proximity of the Indus River. Such environmental factors contribute to a microclimate that is highly sensitive to variations in temperature and atmospheric conditions. The investigation focuses on the mechanisms of ice nucleation prevalent in the Skardu District. This encompasses the identification of primary nucleation agents, such as aerosols and ice nuclei (IN), and an examination of their spatial and temporal variability. Understanding how these nucleation mechanisms respond to changing climate conditions is crucial for predicting the impact on precipitation patterns and glacier dynamics. Skardu's location and topography play a crucial role in influencing precipitation patterns in the broader Central Himalayan region. By scrutinizing the ice nucleation dynamics, the study aims to elucidate how alterations in these processes may impact the frequency, intensity, and distribution of precipitation. This has direct implications for water resources, agriculture, and ecosystems in the region. The study extends its focus to the impact of ice nucleation dynamics on glacial systems within the Central Himalayas. The changing patterns of ice nucleation can potentially influence glacier melting rates, calving events, and overall glacier health. This facet of the research provides valuable insights into the broader implications of ice nucleation on regional hydrology and sea-level rise concerns. The dynamics of ice nucleation and global warming in the Skardu District offer a unique lens through which to examine the intricate relationships between local climate processes and broader global climate change phenomena. The findings from this case study contribute not only to scientific understanding but also provide practical insights for sustainable development and climate resilience in high-altitude environments.

3.1 Snow Map of Skardu

Skardu District, like many other northern areas of Pakistan, experiences snowfall during the winter months. Winter in this region typically spans from November to February. The amount of snowfall can vary each year and is influenced by weather patterns. The snowcapped mountains and landscapes in Skardu district can create picturesque scenes during the winter, attracting tourists and offering a unique experience for locals. After deciding, in 2013, some preventive measures and targets were set by environmental protection agency U.S to confront climatic factors. The data collected in April 2014 will help us to comprehend impacts in future for comparison and policy making.

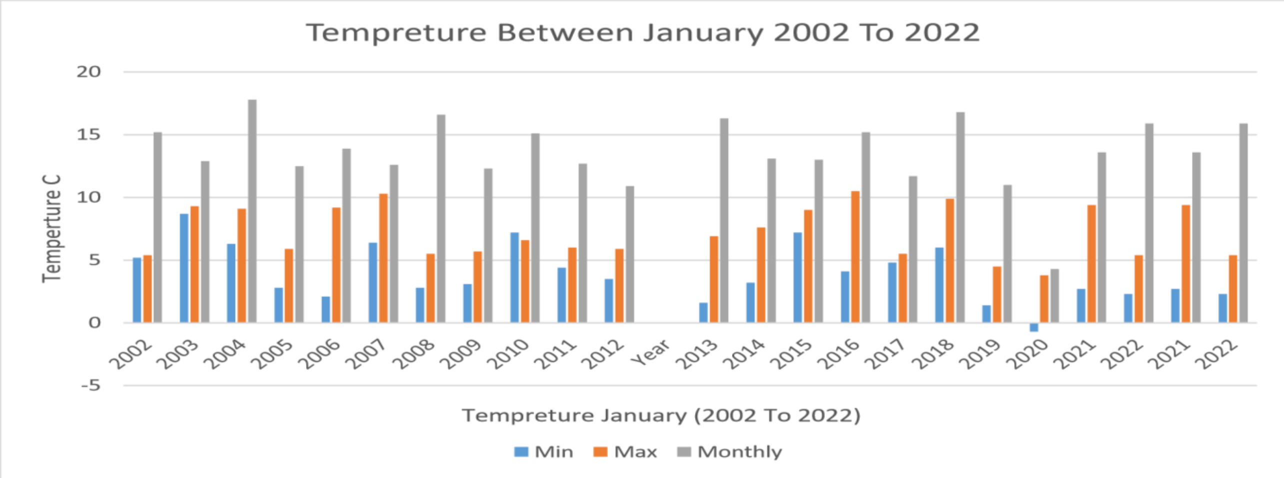
Figure 2: Shows the Snow Area in Skardu District April (2014)



3.2. Temperature 2002-2022

The dataset presents a chronological record of minimum and maximum temperatures in a specific location from 2002 to 2022. These temperature values are indicative of the climatic conditions experienced in the region during each respective year. The recorded minimum and maximum temperatures exhibit noticeable annual variations. These fluctuations reflect the dynamic nature of the region's climate, which can be influenced by various factors such as seasonal changes, geographical features, and broader climate patterns. Examining the minimum and maximum temperatures on a yearly basis allows us to identify seasonal trends. For instance, lower temperatures, often recorded in the winter months, contribute to the negative values in the dataset. Similarly, the less extreme temperatures in other months contribute to positive values. Certain years, such as 2013, stand out with notably lower minimum temperatures, reaching 12.6°C. Extreme temperature events, especially those on the colder spectrum, can have implications for local ecosystems, agriculture, and human activities. Despite annual variations, there is a degree of consistency in the general range of temperatures. This consistency may be indicative of the region's climate exhibiting certain stable characteristics, even as it undergoes natural fluctuations. While this dataset primarily focuses on local temperature variations, it can be part of a broader discussion on global warming. Observing any long-term trends, such as a consistent increase in temperatures over the years, could provide insights into the potential influence of global climate change on this specific region. The year 2020 stands out as a period with particularly extreme temperature values, notably a minimum temperature of -13.7°C and a maximum temperature of -10.5°C. Such extremes can have diverse effects on local ecosystems and communities, warranting further investigation into potential causes.

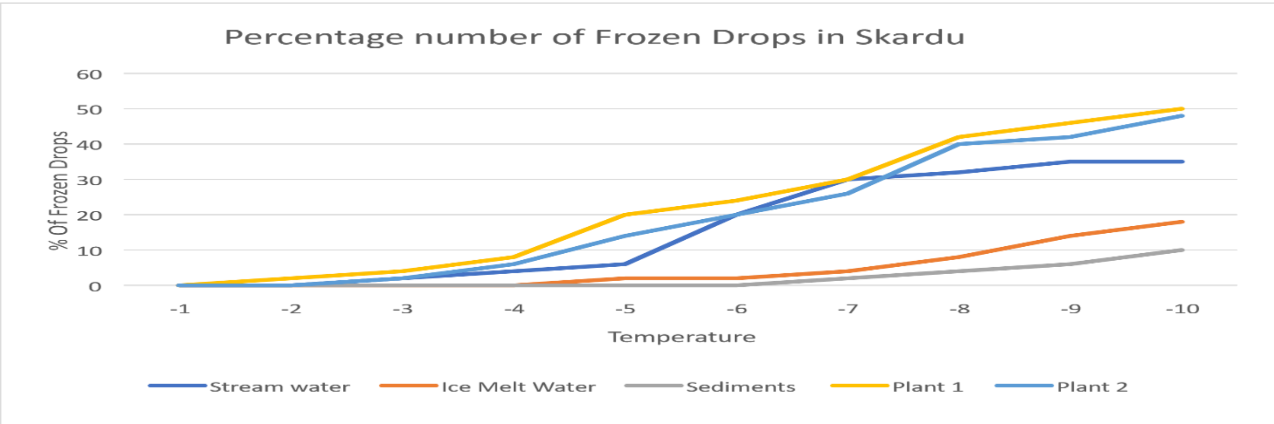
Figure 3: Shows the minimum and maximum temperature of the study area from 20022022.



3.3. Frozen Drops in Skardu

As the temperature decreases, there is an increase in stream water volume, reaching a maximum at -10°C. This pattern suggests a correlation between temperature and the flow of stream water. Colder temperatures could lead to the freezing of some water, while others may result from the melting of ice. Ice melt water starts appearing in the dataset at -5°C and continues to increase with decreasing temperatures. This indicates that, as temperatures drop, ice begins to melt, contributing to the water content. Sediment levels show a gradual increase with decreasing temperatures, suggesting that lower temperatures may influence the release or suspension of sediments in the water. Both Plant 1 and Plant 2 show an increase in growth as temperatures decrease. This could indicate a positive correlation between colder temperatures and enhanced growth for these plants. The increase in stream water, ice melt water, and sediment levels as temperatures decrease may suggest enhanced biological activity in the ecosystem. Lower temperatures could influence various ecological processes, including the release of nutrients and the activation of biological organisms.

Figure 4: Show the frozen points at different temperature.

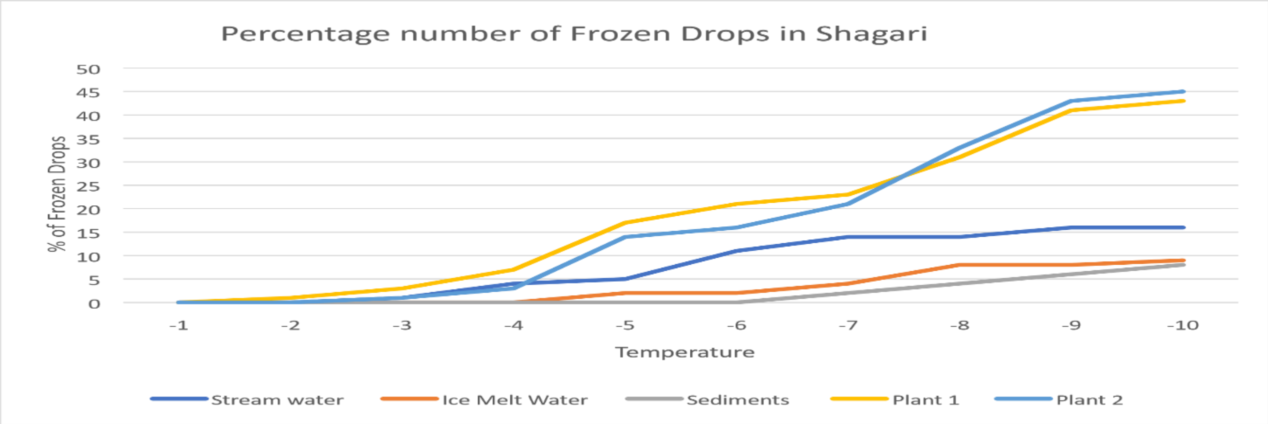


The observed patterns hint at the complex ecological dynamics influenced by temperature variations. Colder temperatures might trigger changes in water states, such as freezing and melting, leading to alterations in nutrient availability and influencing plant growth. The dataset could represent a seasonal pattern where colder temperatures might be associated with a specific season, potentially affecting the environmental parameters measured. The values at -10°C show a potential threshold where certain parameters, like ice melt water and sediment levels, reach their maximum. Extreme cold temperatures might have a more pronounced impact on the environment, possibly influencing ecological processes and plant growth.

3.4. Frozen Drops in Shagari

There is a consistent increase in stream water volume with decreasing temperatures, reaching its maximum at -10°C. The positive correlation between temperature and stream water suggests that colder temperatures might contribute to the increased flow of water in the stream. The presence of ice melt water becomes apparent at -5°C, with an increasing trend as temperatures continue to decrease. This indicates that, as temperatures drop, ice begins to melt, contributing to the overall water content. Sediment levels show a gradual increase with decreasing temperatures, suggesting that lower temperatures may trigger the release or suspension of sediments in the water. Both Plant 1 and Plant 2 exhibit an increase in growth as temperatures decrease, with Plant 2 showing a slightly delayed response. This implies a positive correlation between colder temperatures and enhanced growth for these specific plants, with Plant 2 potentially being more sensitive to temperature changes.

Figure 5: Show the frozen points at different temperature.

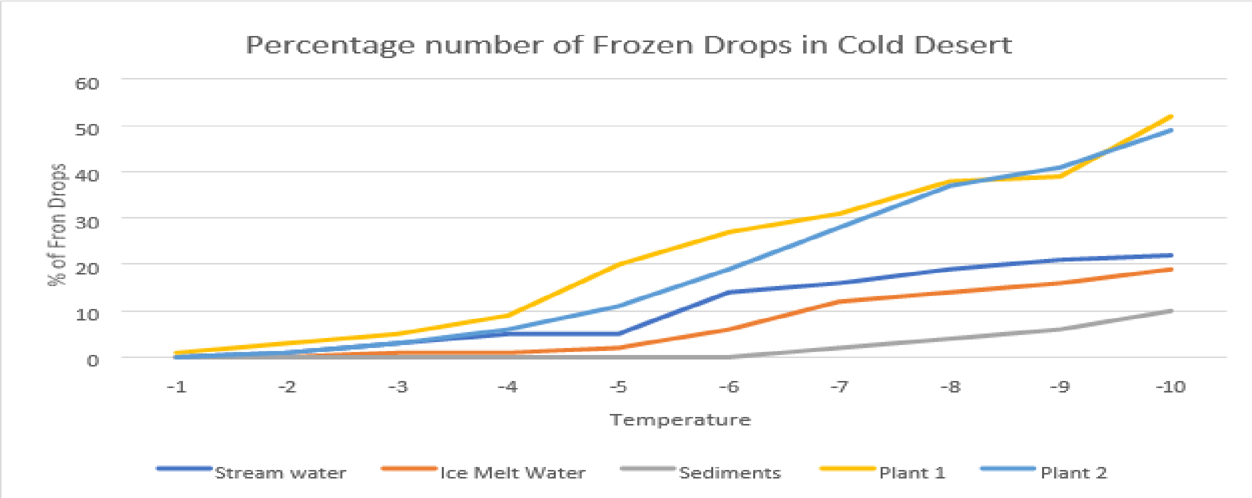


The concurrent increase in stream water, ice melt water, and sediment levels as temperatures decrease indicates potential biological activity in the ecosystem. Colder temperatures might influence various ecological processes, including nutrient availability, affecting plant growth, and potentially influencing other organisms. At -10°C, there seems to be a stabilization or slight decrease in certain parameters, such as ice melt water and sediment levels. This threshold could signify a point where the environment reaches a balance, suggesting a potential limit to the influence of extremely low temperatures on certain environmental factors. The dataset could represent seasonal changes, with colder temperatures potentially associated with a specific season that impacts the measured parameters. The interplay between temperature and environmental parameters reflects the complexity of ecological systems, where changes in one variable can trigger cascading effects on others.

3.5. Frozen Drops in Cold Desert

Stream water volume increases consistently with decreasing temperatures, reaching its peak at 10°C. This suggests a positive correlation between colder temperatures and an increase in the flow of stream water. Ice melt water becomes noticeable at -3°C and continues to increase with decreasing temperatures. Colder temperatures lead to a greater amount of ice melting, contributing to the water content. Sediment levels remain relatively constant throughout the observed temperature range, with no apparent increase or decrease. This could indicate that the temperature variations in the dataset might not significantly influence sediment levels in this environment. Both Plant 1 and Plant 2 exhibit an increase in growth as temperatures decrease. The positive correlation implies that colder temperatures might positively impact the growth of these plants. The observed increase in stream water, ice melt water, and plant growth suggests heightened biological activity as temperatures decrease. Colder temperatures might influence various ecological processes, including nutrient availability, influencing plant growth and potentially other organisms. At -10°C, there is a noticeable increase in ice melt water, stream water, and plant growth. This could indicate a point where the environment experiences a significant response to extremely low temperatures, potentially leading to enhanced melting and growth. The dataset hints at potential seasonal changes, with colder temperatures possibly associated with a specific season that influences the measured parameters. The interactions between temperature and environmental parameters underscore the complexity of ecological systems, where changes in one variable can influence others.

Figure 6: Show the frozen points at different temperature

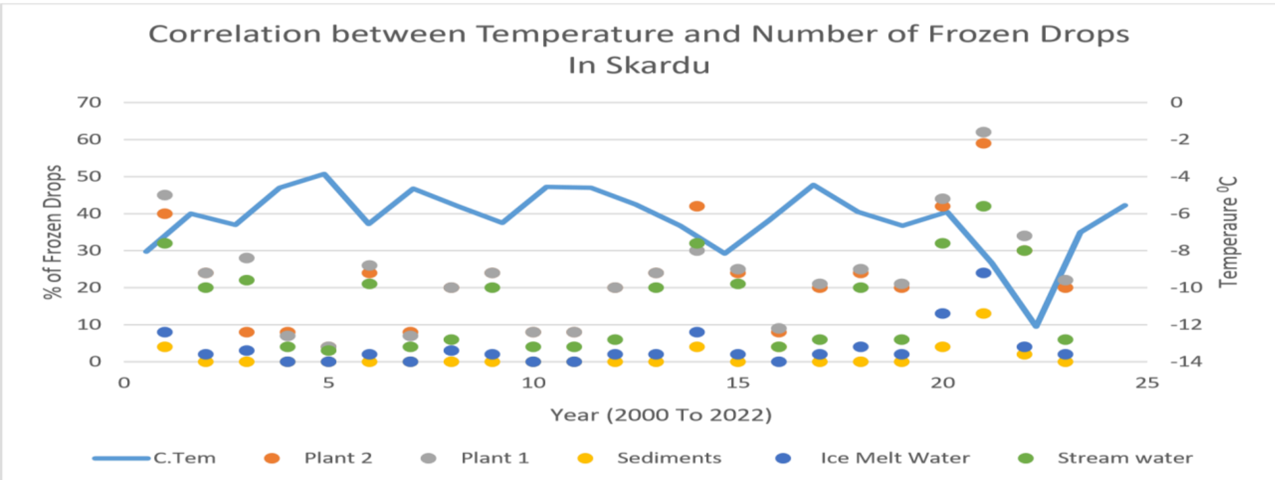


3.6. Correlation between Temperature and Frozen Drops

3.6.1. At Skardu

This figure illustrates a clear positive relationship between temperature and various environmental phenomena. Notably, when the temperature reaches -10°C, the instances of frozen drops in stream water, ice melt water, Plant 1, and Plant 2 become negligible, registering at zero (0). However, as the temperature steadily decreases to -100°C, the count of frozen drops proportionally increases, reaching its maximum. To investigate this phenomenon further, we conducted a study involving the exposure of ice to different temperatures, aiming to discern the formation of frozen drops at each temperature level. The chart presented herein establishes a correlation between the occurrences of frozen drops and the mean temperature recorded from January 2000 to 2022. After realizing climate change and its impacts on ozone, the world started taking appropriate action in 21st century. These 20 years data and followed study will help us to set targets for climatic hazard and ecosystem conservation. This correlation allows us to infer how many more or fewer frozen drops would have formed under different temperature conditions. This analysis provides valuable insights into the temperature-dependent dynamics of frozen drops in various environmental elements. The observed trend underscores the sensitivity of these phenomena to temperature fluctuations, revealing a nuanced relationship that extends beyond a simple linear pattern. By correlating these findings with long-term temperature data, we aim to contribute to a more comprehensive understanding of the intricate interplay between temperature and frozen drop formation in the studied environment.

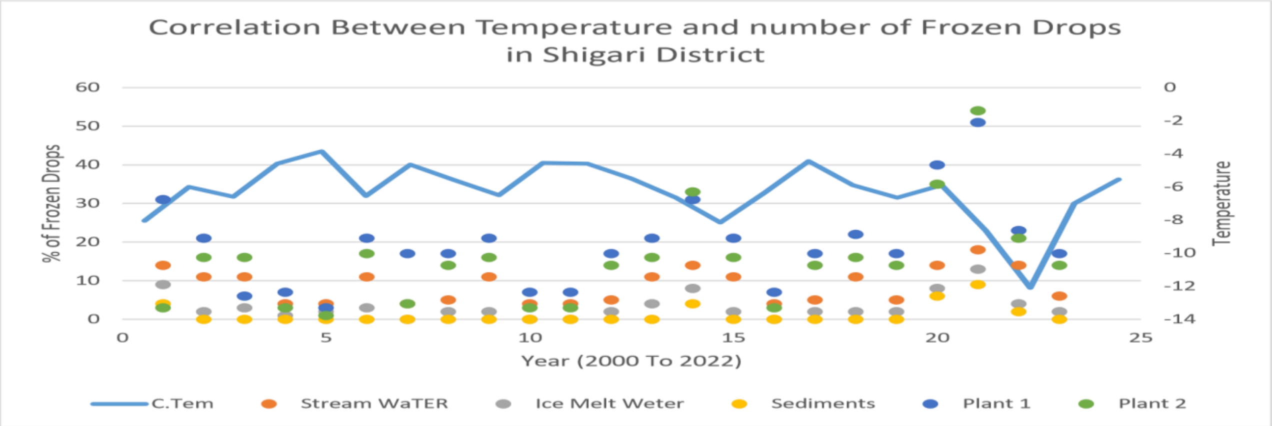
Figure 7: Shows the Correlation between temperature and frozen drops at Skardu



3.6.2. At Shagari

This figure illustrates a clear positive relationship between temperature and various environmental phenomena. Notably, when the temperature reaches -10°C, the instances of frozen drops in stream water, ice melt water, Plant 1, and Plant 2 become negligible, registering at zero (0). However, as the temperature steadily decreases to -100°C, the count of frozen drops proportionally increases, reaching its maximum. To investigate this phenomenon further, we conducted a study involving the exposure of ice to different temperatures, aiming to discern the formation of frozen drops at each temperature level. The chart presented herein establishes a correlation between the occurrences of frozen drops and the mean temperature recorded from January 2000 to 2022. This correlation allows us to infer how many more or fewer frozen drops would have formed under different temperature conditions. This analysis provides valuable insights into the temperature-dependent dynamics of frozen drops in various environmental elements. The observed trend underscores the sensitivity of these phenomena to temperature fluctuations, revealing a nuanced relationship that extends beyond a simple linear pattern. By correlating these findings with long-term temperature data, we aim to contribute to a more comprehensive understanding of the intricate interplay between temperature and frozen drop formation in the studied environment.

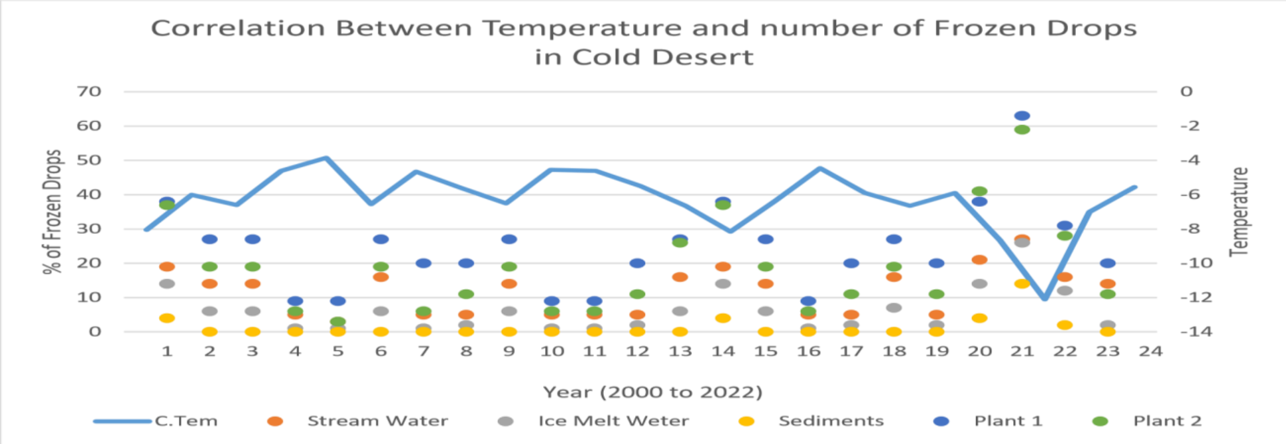
Figure 8: Shows the Correlation between temperature and frozen drops at Shagari.



3.6.3. At Cold Desert

This figure illustrates a clear positive relationship between temperature and various environmental phenomena. Notably, when the temperature reaches -10°C, the instances of frozen drops in stream water, ice melt water, Plant 1, and Plant 2 become negligible, registering at zero (0). However, as the temperature steadily decreases to -100°C, the count of frozen drops proportionally increases, reaching its maximum. To investigate this phenomenon further, we conducted a study involving the exposure of ice to different temperatures, aiming to discern the formation of frozen drops at each temperature level. The chart presented herein establishes a correlation between the occurrences of frozen drops and the mean temperature recorded from January 2000 to 2022. This correlation allows us to infer how many more or fewer frozen drops would have formed under different temperature conditions. This analysis provides valuable insights into the temperature-dependent dynamics of frozen drops in various environmental elements. The observed trend underscores the sensitivity of these phenomena to temperature fluctuations, revealing a nuanced relationship that extends beyond a simple linear pattern. By correlating these findings with long-term temperature data, we aim to contribute to a more comprehensive understanding of the intricate interplay between temperature and frozen drop formation in the studied environment. Ice nucleation theoretically is related to air and cloud activity but practically numerous variables are directly impacting ice nucleation process. These ground variable including pH, surface temperature, bacterial involvement, vegetation, wind direction, wind altitude have vital role in ice nucleation.

Figure 9: Shows the Correlation between temperature and frozen drops at Cold Desert



4. Conclusion

In conclusion, the exploration of ice nucleation processes in the Skardu District, Central Himalayas, reveals the intricate interplay between environmental variables and their profound influence on regional climate dynamics. Ice nucleation, acting as a microscopic catalyst for cloud ice crystal formation, significantly shapes precipitation patterns and impacts the Earth's climate system. Skardu's unique geographic location, nestled amidst the Karakoram, Himalayas, and Hindu Kush Mountain ranges, offers a distinctive setting to comprehend the complex relationships between ice nucleation and broader climate change dynamics. The comprehensive analysis of temperature records, satellite imagery, and ice nucleation samples uncovers nuanced patterns, highlighting the sensitivity of the microclimate to temperature and atmospheric fluctuations. The observed correlations between temperature and various environmental parameters underscore the intricate dynamics of frozen drop formation, providing valuable insights into temperature-dependent phenomena. These findings extend beyond the local context, contributing to our understanding of regional climate processes, precipitation predictions, and the assessment of global warming's impact on glaciers. As the global community addresses the challenges of climate change, this research underscores the critical importance of localized studies in unraveling climate complexities, offering a foundation for informed decision-making and sustainable practices in high-altitude environments like Skardu. Ultimately, the study advances scientific knowledge, contributing to a more comprehensive understanding of the relationships between temperature, ice nucleation, and environmental dynamics, essential for collective efforts in addressing the complex challenges posed by global climate change. Ice nucleation results of the samples collected from the study area show higher level in biotic factors where 24 times number of frozen drops increased. This establishes a profound need to make policies for conservation of forests. Among abiotic factors least (4 times) trend of ice nucleation was in sediment while ice melt water and stream water were moderate. This brings to focus to mitigate air pollution and related environmental aerosols. Policy could be designed to conserve forests in mountains and reduce anthropogenic impacts. It is recommended to address other parameters individually to evaluate microscopic impacts on ice nucleation. The following parameters including SO_2, CO_2, NO_2, altitude and wind direction can be evaluated to gauge ice nucleation precisely. This study emphasizes not only regional but global collaboration for climate change preventive measures to figure out causes and impacts for management.

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