Effects of Cloud Seeding on Hydrological Processes, Air Quality and Particulate Matter Dynamics: A Case Study in San Angelo, TX, United states

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B. S., Northeastern Illinois University, 2020

Master of Arts in The Environmental Sciences, University of Virginia, 2024

A Thesis presented to the Graduate Faculty
of the University of Virginia in Candidacy for the Degree
of Master of Arts

Department of Environmental Sciences

University of Virginia
May 2024

ACKNOWLEDGEMENTS

Completing this Master of Arts thesis within the Department of Environmental Sciences at the University of Virginia has been an extraordinary journey, one filled with challenges, learning, and immense personal and academic growth. This journey, marked by the support and encouragement of many, has culminated in a body of work that I am proud to present. I extend my deepest gratitude to all those who have contributed to this process.

Foremost, I owe a debt of gratitude to my advisor, Dr. Stephan Macko, for his unwavering support, invaluable guidance, and mentorship throughout the course of my research. Dr. Macko's expertise, insightful feedback, and encouragement were instrumental in shaping both the direction and the outcome of this work. His commitment to academic excellence and his genuine care for his students' growth have profoundly impacted my scholarly and personal development.

I would also like to express my sincere thanks to my committee members, whose expertise and feedback have been indispensable. Dr. Robert Davis's thorough reviews and insightful suggestions have significantly enhanced the quality and depth of my research. I am equally grateful to Dr. Ashraf Farahat for his contributions and for bringing a unique and valuable perspective to my work. His guidance has been crucial in refining my thesis.

A special acknowledgment goes to King Fahad University of Petroleum and Minerals, particularly the Department of Physics, for their collaboration and support through Dr. Ashraf Farahat's commitment. This partnership has enriched my research experience and broadened the scope of my academic journey.

My gratitude extends to the Saudi Arabia Ministry of Education for the scholarship that enabled me to pursue my studies at the University of Virginia. This generous support has been instrumental in my academic pursuits and has afforded me the opportunity to grow in a dynamic and international academic environment.

Lastly, but certainly not least, I wish to express my deepest appreciation to my family and friends for their love, encouragement, and unwavering belief in my abilities. Their constant support has been a source of strength and motivation throughout this journey. This thesis stands as a testament to the collective effort and support of everyone mentioned. I am profoundly grateful for your contributions to my academic journey.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

Abstract

Cloud seeding is a weather modification technique aimed at enhancing precipitation from clouds by introducing substances that act as ice nuclei or cloud condensation. This process involves dispersing materials, such as silver iodide or dry ice, into clouds to stimulate the formation of ice crystals or water droplets, ultimately increasing rainfall or snowfall. Space-borne and ground-based data are used to investigate the environmental effects of cloud seeding on air quality and Particulate Matter with a diameter of 2.5 micrometer or less ($PM_{2.5}$) and Particulate Matter with a diameter of 10 micrometer or less (PM_{10}). United States, China, and the United Arab Emirates are considered for this work. Evaluation of cloud seeding's impact on hydrological processes in selected watersheds located in Texas, United States was done to analyze changes in precipitation, runoff, and water availability. Long-term statistical analysis of aerosol optical depth (AOD), Ångström exponent (AE), precipitation, and particulate matter (PM) was performed. Meanwhile, meteorological data including temperature, humidity, pressure, and wind speed/direction are analyzed. Air quality conditions before, during, and after cloud seeding missions are tested using ground monitoring stations. Data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra satellite were also used to perform a statistical correlation between aerosol optical depth (AOD) and ground PM observation. An increase in PM concentration was observed during the cloud seeding missions period, which indicates a possible effect of silver iodide crystals released during the missions by increasing the concentration of PM in the air. The study found that cloud seeding missions have a possible effect on increasing PM_{10} compared to $PM_{2.5}$ concentration, which points to the possible effect of meteorological conditions on washing out silver iodide particles fired during the missions.

CHAPTER 1. CLOUD SEEDING OVERVIEW

1. Historical overview of weather modification.

Weather modification, the act of intentionally altering weather patterns, has a fascinating history that spans from ancient rituals to sophisticated scientific endeavors. This review traces the historical development of weather modification, highlighting key milestones and the evolving scientific understanding that has shaped current practices and debates. The practice of attempting to modify weather dates back to ancient civilizations, where rituals and ceremonies aimed at pleasing gods or spirits were common for invoking rain or favorable weather conditions. These practices, though not based on scientific principles, reflect humanity's longstanding desire to control weather for agriculture and survival.

The scientific pursuit of weather modification began to take shape in the 19th and early 20th centuries. One of the earliest documented scientific attempts was by James Pollard Espy, known as "The Storm King," who in the 1830s proposed a theory that suggested forests could influence rainfall, leading to discussions on altering landscape to modify weather[1]. The modern era of weather modification began in the mid-20th century with the development of cloud seeding techniques. In 1946, Bernard Vonnegut, Irving Langmuir, and Vincent Schaefer discovered that silver iodide could be used to induce snowfall from supercooled clouds, marking the birth of operational cloud seeding[2]. This discovery led to widespread interest and experimentation with cloud seeding, both for research and commercial purposes. Weather modification also found applications in military settings. The most notable example is Operation Popeye during the Vietnam War, where the U.S. military attempted to extend the monsoon season to impede the movement of enemy troops[3]. This operation and others sparked ethical and environmental debates, leading to the 1978 Environmental Modification Convention (ENMOD), which prohibited the use of weather modification for hostile purposes. In recent years, the focus of weather modification research has broadened to include attempts to mitigate the impacts of climate change, such as cloud whitening to reflect sunlight and reduce global warming. However, these newer approaches are subject to intense scientific scrutiny and ethical debate regarding their potential impacts and effectiveness[4].

The history of weather modification is a testament to humanity's enduring fascination with controlling the weather. From ancient rituals to modern scientific methods like cloud seeding and proposals for climate intervention, this field has evolved significantly. Yet, it remains fraught with scientific, ethical, and environmental challenges. As our understanding of the Earth's climate system deepens, the future of weather modification will likely be marked by continued debate and careful consideration of the risks and benefits of intervening in natural processes.

2. Cloud seeding overview

Cloud seeding is a weather modification technique aimed at enhancing precipitation for clouds by introducing substances that act as ice nuclei or cloud condensation nuclei[5]. This process involves dispersing materials, such as silver iodide or dry ice, into clouds to stimulate the formation of ice crystals or water droplets, ultimately increasing rainfall or snowfall.

Cloud seeding has been a subject of scientific exploration for several decades evolving from early experiments to government-supported programs and regional initiatives. Traced back to the early 20th century[6] when pioneering scientists began investigating the possibility of influencing weather patterns. Throughout its development, cloud seeding has showcased potential benefits for water resource management and precipitation enhancement. The most important and notable initial experiments in 1946 in this field are Vincent Schaefer's experiments[7], which involved seeding clouds with dry ice to initiate snowfall, and Irving Langmuir and Vincent Schaefer's in 1946 collaboration[6], leading to the discovery of super-cooled clouds and the impact of seeding on precipitation. Cloud seeding operations have seen notable advancements and increased implementation over the past two decades. During this period, there has been a growing focus on utilizing cloud seeding as a means to address water resource management, enhance precipitation, and mitigate the impacts of drought.

Some governments worldwide recognized the potential of cloud seeding and initiated programs to explore its applications. Previously, the United States (US) Weather Bureau, now NOAA (National Oceanic and Atmospheric Administration) initiated in 1947 Project Cirrus[6], aiming to investigate cloud modification through seeding. They were followed by the National Hail Research Experiment (NHRE) conducted in the 1970s by multiple US agencies to study hail suppression techniques[6].

In order to address water resource management and precipitation enhancement, cloud seeding has been extensively studied and implemented in various regions around the world, including the United States (US) [8–10], China [11],[7], and the Middle East (ME) [12–17]. For example, the Colorado River Basin Cloud Seeding Program was initiated in the 1950s to augment water supply for agricultural and municipal purposes. Moreover, many cloud seeding campaigns have been launched in arid/semiarid regions in the United States (USA), the United Arab Emirates (UAE)[14], the Kingdom of Saudi Arabia (KSA)[18], and China[11] aiming to increase water resources and mitigate drought conditions. In addition, advancements in cloud seeding techniques, such as the use of ground-based generators and aircraft systems, have improved the efficiency and effectiveness of the process. Ongoing research and evaluation are being conducted to better understand the environmental impacts and optimize the outcomes of cloud seeding operations. Overall, cloud seeding has become an increasingly important tool in the quest for sustainable water management and addressing water-related challenges. Regions that have adopted cloud seeding techniques shown in (figure 1 & 2).

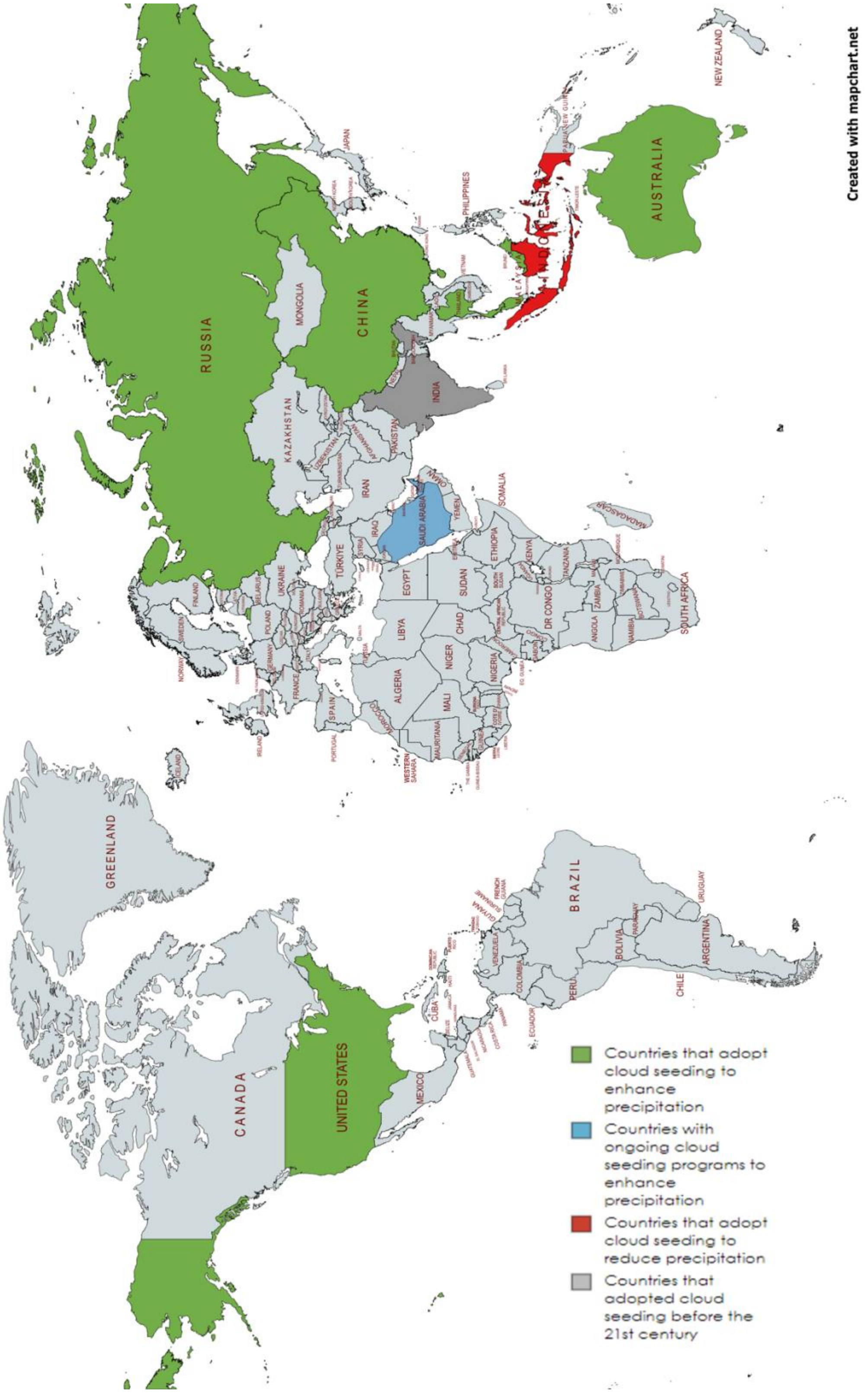
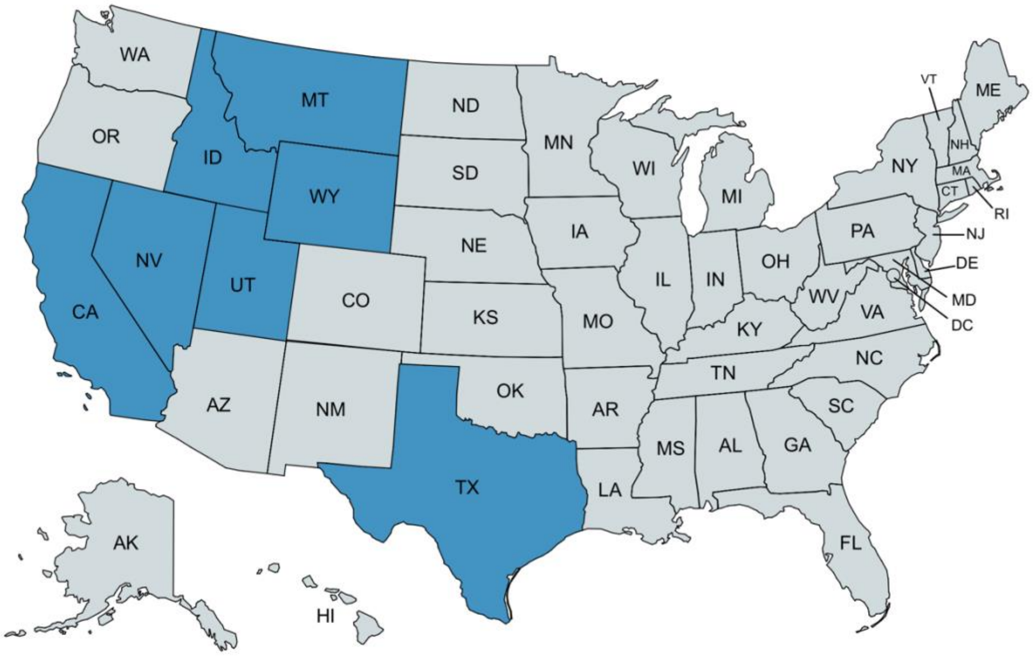


Figure 1. Map of countries that have adopted cloud seeding techniques.



Created with mapchart.net

Figure 2. Map of states that have adopted cloud seeding techniques in USA.

3. Validation techniques

Over the past decades these techniques have been implemented and studied in various regions over the world.

3.1 Using Silver Iodide

Cloud seeding with silver iodide is a commonly used technique in weather modification[7]. Silver iodide particles are dispersed into clouds either by ground-based generators or by aircraft. These particles serve as ice nuclei, which facilitate the formation of ice crystals within the cloud. As a result, the ice crystals can grow and eventually fall as precipitation, enhancing rainfall or snowfall. The effectiveness of cloud seeding with silver iodide is still subject to scientific debate[19]. Other studies have reported positive effects, showing an increase in precipitation in targeted areas[19]. Despite the potential benefits, there are several flaws and limitations associated with cloud seeding using silver iodide. The main issues include environmental impact, uncertainty about long-term effects, and the potential for unintended consequences[20]. The release of silver iodide into the atmosphere raises concerns about its potential impact on the environment, particularly in water bodies and soil. While the quantities used are generally considered to be low and the dispersal is typically at high altitudes, the long-term effects on ecosystems and water quality are still not fully understood[20]. Unintended Consequences: Cloud seeding using silver iodide can potentially lead to unintended consequences such as changes in precipitation patterns, altering natural weather systems, or impacting areas downwind of the seeding location[20].

3.2 Using Hygroscopic Flares

Hygroscopic flares involve the use of flares containing hygroscopic materials, such as potassium chloride or sodium chloride[6] . These flares are ignited in the lower part of clouds, releasing the hygroscopic particles[21]. The particles absorb moisture from the cloud, causing the cloud droplets to grow and potentially leading to increased rainfall. The effectiveness of cloud seeding with hygroscopic flares is still an area of active research and debate. A study has shown mixed results, with some indicating positive effects on precipitation, while others have found limited or no significant impact[5]. Where its effectiveness remains a topic of debate, there is evidence suggesting that cloud seeding can enhance precipitation under certain meteorological conditions. Research conducted by the National Center for Atmospheric Research (NCAR) in the USA has indicated that cloud seeding can increase precipitation by 5–15% in targeted areas[9]. The World Meteorological Organization (WMO) recognizes cloud seeding as a viable technology for weather modification but emphasizes the need for rigorous scientific studies and careful evaluation of its environmental and societal impacts.

Over the years, advancements have been made in cloud seeding techniques and materials used. Some notable developments including: Introduction of silver iodide as a common cloud seeding agent due to its ice nucleating properties, development of ground-based generators and aircraft systems for dispersing cloud seeding agents, and the use of hygroscopic materials (e.g., potassium iodide) for cloud seeding to enhance rainfall.

4. The gap in the knowledge

The exploration of cloud seeding's impact on hydrological processes, Aerosol Optical Depth (AOD), air quality, and particulate matter in the air reveals critical gaps in our current understanding, necessitating further research in these areas. The relationship between cloud seeding and air quality, particularly its impact on particulate matter (PM) concentrations, is underexplored. While cloud seeding is designed to induce rainfall and could theoretically wash out airborne pollutants, its actual effects on PM distribution and concentration levels are not well-documented. This gap is critical, given the known health risks associated with particulate pollutants[22]. Specifically concerning particulate matter, there's a need for targeted studies that examine how cloud seeding influences the size distribution, composition, and overall concentration of particulate matter in the air. Such research is crucial for assessing the broader environmental health implications of cloud seeding[23]. The impact of cloud seeding on Aerosol Optical Depth (AOD) is poorly understood. Cloud seeding could potentially alter the aerosol composition in the atmosphere, thereby affecting AOD readings. This change could have implications for climate modeling and air quality predictions, yet research in this area remains limited[24]. The ecological impacts of cloud seeding, especially on watershed ecosystems and water availability, require further investigation. Understanding these impacts is essential for evaluating the sustainability and environmental consequences of cloud seeding operations, particularly in regions dependent on precise water management strategies. There is a significant gap in quantitatively understanding the impact of cloud seeding on hydrological cycles. While some studies have modeled the potential influences on precipitation patterns, empirical data on the long-term effects on surface and groundwater systems are scarce[25]. Beyond environmental and scientific considerations, there's a need to better understand the socioeconomic impacts of cloud seeding, including public perception and regulatory aspects. This encompasses analyzing the cost-benefit ratios of cloud seeding projects and their acceptance among local populations and policymakers. Addressing these gaps through multidisciplinary research could significantly advance our understanding of cloud seeding's impacts, leading to more effective and environmentally responsible weather modification strategies.

5. Purpose and objective of the Research

The primary purpose of this research is to comprehensively understand the impacts of cloud seeding on hydrological processes, air quality, and particulate matter dynamics, focusing on a case study in San Angelo, Texas. This investigation seeks to bridge the existing knowledge gap concerning the efficacy and environmental consequences of cloud seeding operations. It aims to scrutinize both the scientific foundations and the ethical considerations of weather modification practices, particularly cloud seeding, to enhance precipitation and address water scarcity issues. Through a detailed examination of cloud seeding's direct and indirect effects on atmospheric composition, precipitation patterns, and watershed health, this research endeavors to provide a balanced and evidence-based perspective on the utility and sustainability of cloud seeding as a weather modification tool.

The objective of the research is to explore the ethical and scientific considerations surrounding cloud seeding. This objective aims to address the ethical dilemmas and scientific skepticism associated with cloud seeding. It involves analyzing the perspectives of various stakeholders, including scientists who question the effectiveness of cloud seeding methods. By achieving these objectives, the research intends to provide a nuanced understanding of cloud seeding's role in weather modification, its potential benefits, and its limitations, thereby informing future decisions in the field of environmental management and policy-making. The study also aims to investigate the impact of cloud seeding on precipitation enhancement. Leveraging literature reviews and precipitation data from WTWMA and NASA records, this objective aims to critically assess previous studies that claim successful precipitation enhancement through cloud seeding. The analysis will include a detailed review of precipitation patterns in San Angelo, TX, before and after cloud seeding events. As well as analyzing the relationship between cloud seeding, Aerosol Optical Depth (AOD), and Particulate Matter Dynamics. This involves a comparative study of AOD and particulate matter before and after cloud seeding operations, incorporating a literature review and case studies from the United Arab Emirates and China. The case study in San Angelo, TX, will specifically focus on the changes in AOD, Ångström exponent, and particulate matter dynamics as a result of cloud seeding activities. Another object is to assess the impact of cloud seeding on hydrological processes and watersheds. This objective seeks to understand how cloud seeding influences water availability, watershed health, and hydrological cycles in the targeted area. It involves analyzing the outcomes of cloud seeding on local water resources, with a focus on San Angelo, TX. Beside examine the factors influencing the dynamics of aerosols and particulate matter in relation to cloud seeding. This includes an evaluation of geographical location, meteorological conditions, existing air pollution levels, cloud seeding techniques, and local topography as factors that affect the success of cloud seeding and its impact on atmospheric aerosols and air quality.

6. Scientific considerations about the effectiveness of cloud seeding.

Reviewing the effectiveness of cloud seeding in enhancing precipitation reveals a nuanced picture, with several studies and scientific evaluations casting doubt on its efficacy. This skepticism is grounded in empirical research, methodological critiques, and the inherent variability of weather patterns. A comprehensive review by the National Research Council (NRC) in 2003 highlighted the inconclusive evidence regarding the effectiveness of cloud seeding (National Research Council, 2003, "Critical Issues in Weather Modification Research"[25]). The report indicated that despite decades of research, there remained "no convincing scientific proof" of the efficacy of cloud seeding in inducing rainfall due to lack of consistent evidence. A Review of Cloud Seeding Experiments to Enhance Precipitation and Some New Prospects in the Bulletin of the American Meteorological Society, discussed the significant methodological challenges in proving cloud seeding effectiveness. These include the difficulty in isolating the effects of seeding from natural variability in precipitation, which makes it hard to attribute any changes in rainfall patterns directly to cloud seeding efforts[22]. Another study pointed out the lack of statistical significance in many cloud seeding experiments. The authors argued that many studies failed to demonstrate a clear and statistically significant increase in precipitation that could be directly attributed to cloud seeding[26]. Concerns about the environmental impact of cloud seeding agents, such as silver iodide, have been raised, questioning the sustainability of cloud seeding. Moreover, ethical considerations about the manipulation of weather patterns and its potential impacts on neighboring regions add another layer of complexity to the debate. The economic feasibility of cloud seeding is also a significant concern. A study argues that the costs associated with cloud seeding operations may not justify the marginal increases in precipitation, especially considering the opportunity costs and potential investments in alternative water resource management strategies[27]. In conclusion, the skepticism surrounding cloud seeding's effectiveness in enhancing precipitation is well-founded in scientific literature and research. The challenges of demonstrating consistent and statistically significant outcomes, coupled with methodological limitations, environmental, ethical considerations, and questions about economic feasibility, all contribute to a cautious stance on the utility and value of cloud seeding as a reliable weather modification technique. Further research, particularly in the form of controlled, randomized experiments with rigorous statistical analysis, is necessary to clarify the potential and limitations of cloud seeding in water resource management.

7. Ethical considerations

The intentional modification of weather patterns, including cloud seeding, raises significant ethical considerations due to its potential for unforeseen consequences. When altering natural weather patterns, particularly through large-scale interventions like cloud seeding, there is a risk of impacting neighboring regions or ecosystems in ways that are not fully understood[28]. Intentional weather modification can lead to unpredictable outcomes, affecting not only the targeted region but also neighboring areas. Changes in precipitation patterns or alterations to natural weather systems can have cascading effects on ecosystems, agriculture, and water resources, potentially disrupting the delicate balance of regional environments[29]. The ethical considerations of intentionally modifying weather patterns revolve around the potential for harm to ecosystems, human populations, and the environment. In some cases, the benefits of weather modification for one region may come at the expense of negative impacts on others, leading to questions of fairness and equity, for example, in China, weather modification experiments were blamed for snow blizzard which killed at least 40 people[30]. Another ethical concern is the lack of consent from individuals or communities who may be affected by the consequences of weather modification. Neighboring regions may not have a say in the decision to alter weather patterns, yet they could bear the brunt of any negative impacts[31].

CHAPTER 2. ENHANCEMENT OF PRECIPITATION BY CLOUD SEEDING METHODS.

1. Review of participation enhancement by cloud seeding

In Texas, USA there were many operations reported and evaluated since 2015 in San Angelo [10](Table 1). It can be shown that the percentage of rainfall increase ranges between 9 – 20%. Other cloud seeding campaigns have been performed in Wyoming[9], Idaho[32], and Utah[8], USA and showed an increase in precipitation (Table 2).

Table 1. Cloud seeding campaigns (2015 – 2022) in San Angelo, TX, USA6. Percent (%) represents the increase of precipitation and cloud mass[10].

Year	# of clouds	# of days	Percent (%)
2015	88	38	10
2016	111	32	9
2017	73	24	10
2018	54	21	12
2019	61	31	18
2020	56	27	20
2021	62	33	14
2022	54	26	17

Table 2. Cloud seeding campaigns in Wyoming, Idaho, and Utah, USA. Percent (%) represents the increase of precipitation and cloud mass.

Location	Year	Percent (%)
Wyoming [9]	2007 – 2011	5 – 15
Idaho [32]	2003 – 2022	4 – 7.1
Utah[8]	2021 - 2022	3 – 21

Tasmania, Australia has been experimenting with cloud seeding since the 1960s [33], the reports stated that the efforts of cloud seeding enhancement have been raising rainfall 5 – 14% more than expectation. However, in Snowy Mountains region in January, 2020, operation of cloud seeding was initiated, two weather stations received major fire damage, where no cloud seeding generators were on site at the time of the fires[19] .

China has been actively engaged in cloud seeding operations to address water scarcity and enhance precipitation [7,11]. As one of the world's largest users of cloud seeding technology, China has implemented extensive programs across various regions. For instance, the country has focused on cloud seeding in arid areas, such as the northwestern provinces, to combat drought and increase water resources. China's cloud seeding operations have involved the deployment of aircraft or ground-based generators to disperse cloud seeding agents[11] , primarily silver iodide, into targeted clouds. While specific data on the outcomes of these operations may vary, studies have indicated that cloud seeding in China has contributed to notable increases in precipitation. The Henan region[19] operation record 12.8 – 13.8% increase in rainfall, and the Fujian Gutianin region operation recorded 24.16% increase in rainfall.

Cloud seeding operations in the Medial East (ME) have gained significant attention as countries in the region face water scarcity challenges. Several nations, including the UAE, and KSA, have implemented cloud seeding programs to increase rainfall and enhance water resources. The ME arid climate makes cloud seeding a valuable tool in addressing water shortages and supporting agricultural activities. In the UAE, for example, the National Center of Meteorology (NCM) has been actively involved in cloud seeding initiatives since the early 2000s[14] . The country employs aircraft and ground-based generators to disperse cloud seeding agents, primarily using silver iodide, into suitable clouds[6]. While the effectiveness and precise impact of these operations vary depending on weather conditions, studies have reported positive results, including increased rainfall and improved water availability. The ongoing commitment to cloud seeding in the ME demonstrates the region's dedication to sustainable water management and addressing water scarcity challenges.

The UAE has been at the forefront of cloud seeding efforts, utilizing advanced techniques to enhance precipitation and address water scarcity[6]. Recognizing the importance of water resources in sustaining various sectors of the economy, the UAE has invested significantly in cloud seeding programs. NCM plays a crucial role in overseeing and implementing these initiatives. The UAE employs a combination of ground-based generators and aircraft to disperse cloud seeding agents, primarily silver iodide, into suitable clouds. These efforts aim to stimulate the formation of ice crystals and subsequent precipitation. Where as the effectiveness of cloud seeding can vary due to weather patterns and cloud conditions, studies have shown promising results. For instance, research conducted by the NCM and other institutions has indicated an increase in precipitation ranging from 5 – 30% in targeted areas. Cloud seeding in the UAE has particularly focused on enhancing rainfall during the country's rainy season, which typically occurs between November and March[14] . By actively leveraging cloud seeding technology, the UAE demonstrates its commitment to sustainable water management, ensuring a more reliable water supply for agriculture, domestic use, and other vital sectors[6].

Cloud seeding is an important tool in KSA efforts to enhance precipitation and mitigate water scarcity. The country has implemented significant cloud seeding programs to increase rainfall and improve water resources[17]. The Saudi Ministry of Environment, Water, and Agriculture oversees these initiatives, working in collaboration with research institutions and international partners[34]. The KSA utilizes aircraft and ground-based generators to disperse cloud seeding agents, primarily silver iodide, into clouds[35]. This process aims to stimulate the formation of ice crystals and subsequently enhance precipitation. While specific data on the outcomes of cloud seeding in KSA may vary, studies have shown promising results[17].

One study analyzed the impact of cloud seeding operations on rainfall patterns. The study found that cloud seeding had a positive impact[36], resulting in an increase in rainfall in the targeted areas. These findings highlight the effectiveness of cloud seeding in KSA and its potential for addressing water scarcity challenges. The ongoing commitment to cloud seeding in the country underscores its dedication to sustainable water resource management.

Weather Modification Inc. conducted cloud modification operations in the Asir region of Saudi Arabia with the aim of increasing precipitation from convective clouds[17]. The effectiveness of the modification was assessed by comparing 28 seeded clouds with 49 naturally developing clouds using radar measurements of cloud characteristics[17]. The results shows that the seeded clouds had higher reflectivity and greater precipitation flux compared to the natural clouds[17]. The difference in maximum reflectivity between the two groups was statistically significant, while the difference in maximum precipitation flux was marginally significant. These findings align with recent scientific literature on cloud modification. The cloud modification process accelerated precipitation generation compared to natural development, but some modified clouds continued to develop, resulting in a delayed peak precipitation. It is worth mentioning that the study did not involve random selection of clouds, but it demonstrated that modified clouds exhibited significantly higher reflectivity and precipitation rates compared to those developing naturally[17].

The effectiveness of cloud seeding techniques can vary depending on meteorological conditions such as cloud type, temperature, moisture content, and the landscape of the target region. Moreover, previous research[37] , has highlighted the importance of understanding the microphysical processes involved in cloud seeding and their subsequent influence on precipitation formation[37]. It is challenging to accurately predict and control these conditions, leading to inconsistent results[37]. To assess the impact of cloud seeding on hydrological processes, it is crucial to consider various factors such as atmospheric conditions, cloud dynamics, and the geographical characteristics of the target region. For example, another study[21] analyzed the impact of cloud seeding on precipitation in the Mount Hermon region and found a significant increase in rainfall downwind of the seeded clouds. Similarly, a study[38] examined the effects of cloud seeding on snowfall in the Sierra Nevada mountains and observed a substantial increase in snowpack accumulation.

2. Analyzing precipitation enhancement in San Angelo, TX.

2.1. Introduction.

Precipitation plays a vital role in the Earth's water cycle, influencing various aspects of our environment and ecosystems. Understanding the factors that affect precipitation patterns is essential for effective water resource management and weather modification techniques such as cloud seeding. Cloud seeding operations aim to enhance precipitation by introducing additional particles into clouds, altering their microphysical properties and potentially increasing rainfall in targeted areas. The purpose of doing this is to analyze precipitation data obtained through the Global Precipitation Measurement (GPM) mission in locations where cloud seeding operations occur. The GPM satellite mission provides valuable insights into global precipitation patterns, offering high-resolution data with global coverage[39]. By utilizing the GPM data, we aim to investigate the impact of precipitation on aerosol levels in the atmosphere. Aerosols, comprising solid or liquid particles suspended in the atmosphere, have the potential to influence cloud formation, precipitation processes, and overall atmospheric dynamics[40]. Understanding the relationship between aerosols and precipitation is crucial for comprehending the complex interactions within the atmosphere and their implications for weather modification strategies.

To assess this relationship, we will employ the Giovanni platform[41]. The Giovanni platform allows us to access and analyze GPM precipitation data, combining it with other relevant atmospheric variables, such as aerosol measurements, to investigate the interplay between precipitation and aerosol levels. The aim is to contribute to the understanding of the dynamics between precipitation, cloud seeding operations, and aerosol concentrations in the atmosphere. By analyzing the GPM precipitation data in cloud seeding operation locations, we can evaluate the impact of enhanced rainfall on aerosol levels and explore the potential feedback mechanisms between these variables.

2.2. Study Area

San Angelo, TX, USA is a vibrant city known for its rich history and cultural heritage. Tom Green is a county located in San Angelo which encompasses a diverse landscape, featuring beautiful rivers, rolling hills, and expansive plains. Cloud seeding campaigns in Tom Green involves dispersing various substances into the clouds to enhance precipitation. This process aims to stimulate rainfall and mitigate the impact of droughts in the area. Cloud seeding operations in Tom Green County are designed to bolster the local water supply and support agriculture, especially during times of reduced rainfall. By introducing additional particles into the clouds, scientists and weather experts attempt to encourage the formation of raindrops and increase the chances of precipitation. These cloud seeding efforts demonstrate the community's proactive approach to managing water resources and ensuring sustained agricultural productivity. The operations serve as a testament to the region's commitment to innovation and environmental sustainability. Tom Green County, with its cloud seeding operations[10], showcases how local communities are employing scientific techniques to address water scarcity challenges and foster a more resilient and prosperous future.

The evaluation reports from 2015 – 2020 provide insights into the cloud seeding operations in the Tom Green County. Here is a summary of the findings:

Table 3. Cloud seeding campaigns in Tom Green, San Angelo, TX, USA. Percent (%) represents the increase of precipitation and cloud mass

Year	# of seeded clouds	Percent (%)
2015	88	89 – 135%
2016	111	85 – 125%
2017	73	8 – 115%
2018	54	19 – 150%
2019	61	7 – 105%
2020	56	15 – 120%

Overall, these evaluation reports demonstrate the effectiveness of cloud seeding operations in increasing precipitation and cloud mass in the San Angelo area. The specific impacts varied across years and cloud types, but the findings generally highlight positive outcomes from the cloud seeding efforts conducted in Tom Green County during this period.

2.3. Global Precipitation Measurement (GPM) Mission

The Global Precipitation Measurement (GPM) mission is an international initiative aimed at improving our understanding of global precipitation patterns and their impact on Earth's water cycle[39]. Launched on February 27, 2014, GPM is a collaboration between NASA and the Japan Aerospace Exploration Agency (JAXA), with contributions from other international partners. The mission utilizes a constellation of satellites and ground-based sensors to provide high-quality global precipitation data[39]. To accurately measure precipitation, GPM employs a dual-frequency precipitation radar (DPR) and a microwave imager (GMI) aboard the GPM Core Observatory satellite[39]. The DPR is capable of providing detailed three-dimensional measurements of precipitation particles, while the GMI detects microwave radiation emitted by precipitation[39]. These instruments work together to provide comprehensive and precise information about the distribution, intensity, and structure of precipitation systems worldwide.

2.3.1 Applications and Benefits of GPM

The data collected by GPM has a wide range of applications and benefits in various fields. In weather forecasting, GPM data plays a crucial role in improving precipitation estimates and enhancing the accuracy of weather models. By providing real-time and accurate information about rainfall rates and storm intensities, GPM enables meteorologists to issue more reliable and timely forecasts, enhancing early warning systems for severe weather events[39]. Furthermore, GPM data is invaluable for hydrological and climate studies. It contributes to a better understanding of the water cycle, including the processes of evaporation, condensation, and precipitation. By monitoring global precipitation patterns, GPM helps researchers assess changes in rainfall distribution, which is essential for studying climate variability and long-term climate trends[39].

2.3.2. The use of GPM for utilizing aerosol analysis in cloud seeding operations

Cloud seeding operations involve the introduction of certain aerosol particles into clouds to enhance precipitation[42]. GPM data can contribute to this process by providing insights into the behavior and characteristics of clouds, such as their vertical structure, precipitation intensity, and spatial distribution[39]. By analyzing GPM data in conjunction with aerosol measurements, researchers and cloud seeding practitioners can gain a better understanding of how aerosols interact with clouds and influence precipitation processes. GPM's ability to provide accurate and detailed information about precipitation systems allows for the identification of suitable cloud seeding targets. By combining aerosol analysis with GPM data, researchers can assess the impact of aerosols on cloud properties and precipitation efficiency, helping to identify specific cloud types or regions where cloud seeding operations may be more effective[42].

2.4. Data analysis

Based on West Texas Weather Modification Association (WTWMA) reports [11], the precipitation before and after seeding operation was calculated for small, large, and type B clouds, however, It is not clear WTWMA classified clouds based on what[10], based on scientific reviews, there was not any scientific paper provides the classification of the clouds used by WTWMA. The annual evaluations reports provided by WTWMA recorded the enhancement percentage of precipitation and the average annual rainfall, the average amount of rainfall was compared to precipitation data provided by GPM and used as bassline to calculate the estimated precipitation without seeding scenario. The percentage of increased precipitation and the amount that was expected before and after the cloud seeding campaign. (Table 4).

Table 4. Precipitation amount and enhancement percentage by cloud seeding operations in West Texas from 2015 – 2020. Y: Yes, N: No.

		Type of the cloud						
Year	Scenario	Small		Large		Type B		
		Precipitation						
		Increasing Percent	Amount	Increasing Percent	Amount	Increasing Percent	Amount	Total
	Seeding	(%)	mm	(%)	mm	(%)	mm	mm
2015	Y	135	26.024	89	126.99	10	79.2	232.22
	N		11.074		67.19		72.00	150.27
2016	Y	125	23.40	58	113.05	7	71.84	208.29
	N		10.40		71.55		67.14	149.09
2017	Y	115	22.62	40	122.85	8	72.90	218.37
	N		10.52		87.75		67.50	165.77
2018	Y	150	32.50	79	114.88	19	47.60	194.98
	N		13.00		64.18		40.00	117.18
2019	Y	105	33.58	64	114.67	7	214.00	362.25
	N		16.38		69.92		200.00	286.30
2020	Y	120	17.68	43	104.09	9	93.26	225.03
	N		12.58		72.79		85.56	170.93

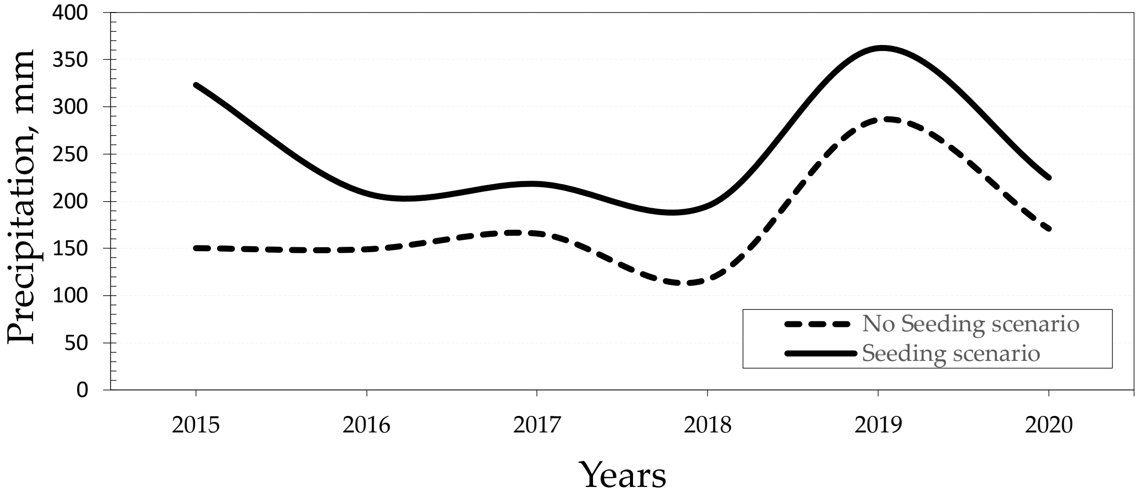


Figure 3. Comparison of total precipitation (mm) calculated during cloud seeding and without cloud seeding scenarios in Tom Green, TX during 2015 – 2020.

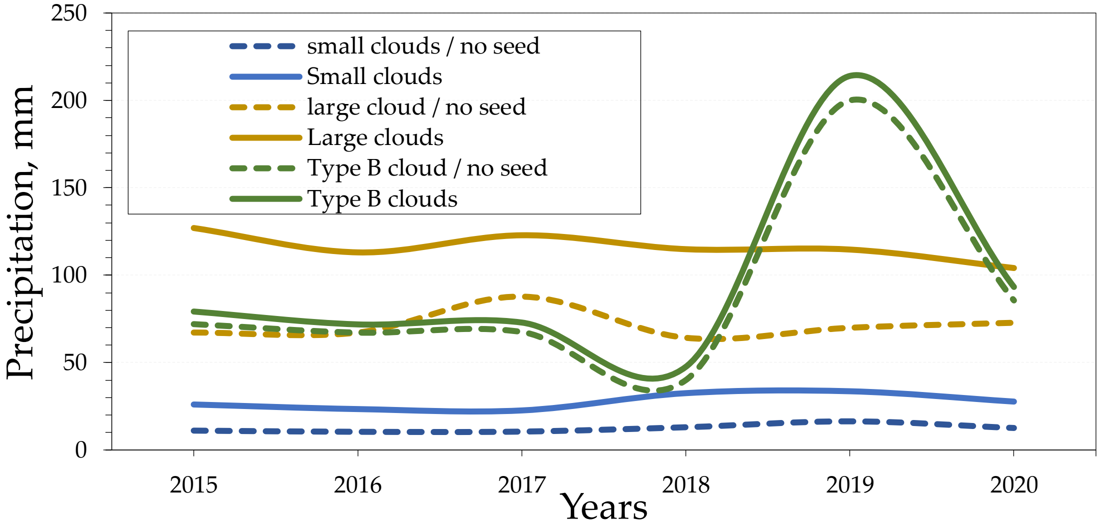


Figure 4. Average precipitation during seeding seasons for the estimated precipitation before seeding scenario and the resulted precipitation after seeding for the three clouds types.

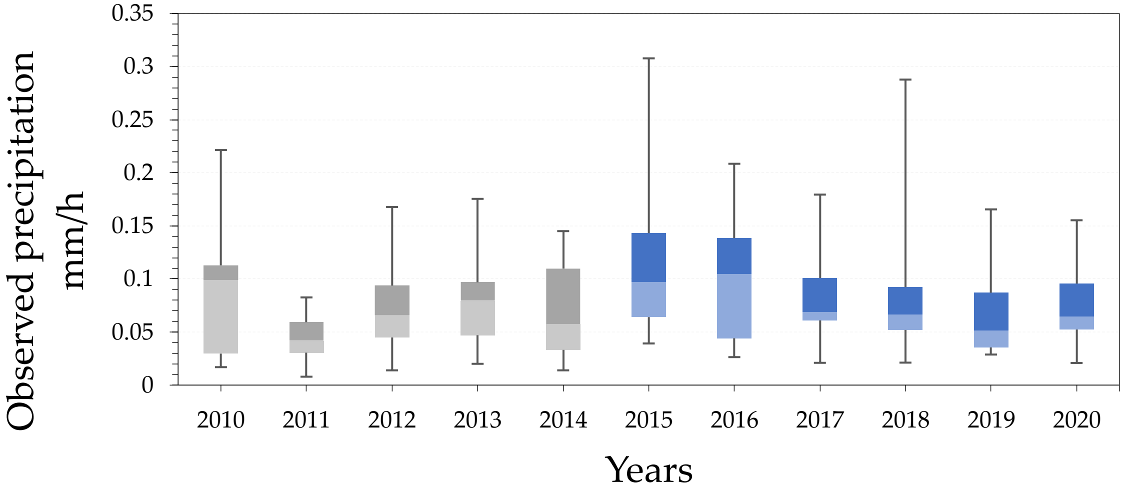


Figure 5. Annual Area Averaged Precipitation rate (mm/h) in Tom Green County before and after cloud seeding campaigns, gray boxes represent period before seeding and blue boxes represent seeding period. These data was observed using GPM satellite.[41]

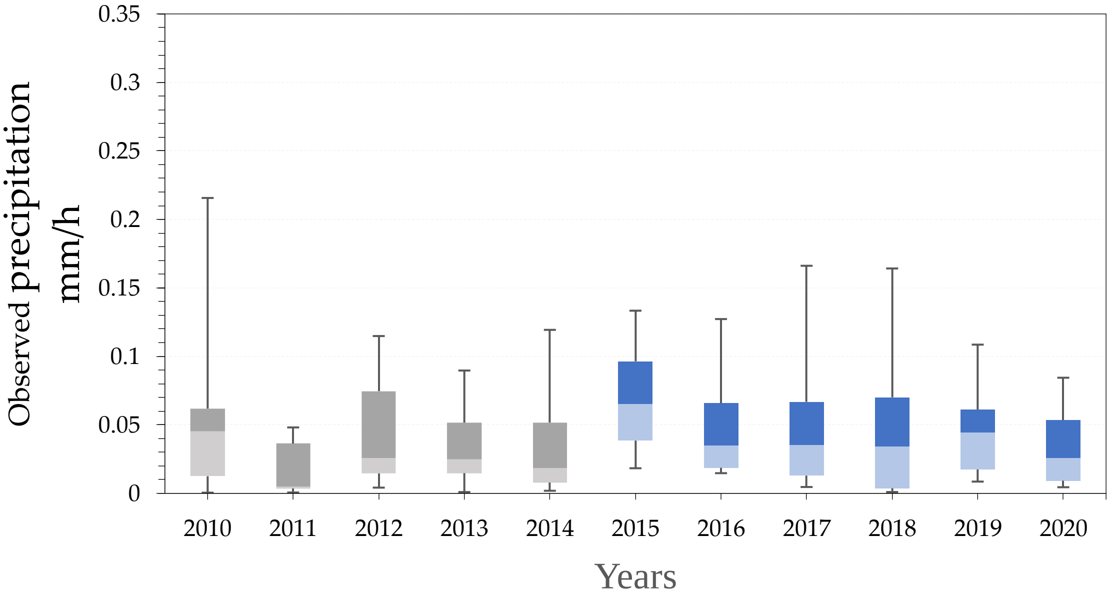


Figure 6. Annual precipitation rate (mm/h) in Pecos County in TX from 2010 to 2020 (unseeded area), gray boxes represent period before seeding and blue boxes represent seeding period. These data were observed using GPM satellite.

In figures 5 and 6, the comparison between the average precipitation in Tom Green County, where cloud seeding missions occur, and Pecos County, where there are no cloud seeding missions, was conducted. This analysis aimed to estimate the rate of rainfall change between the periods before and after the implementation of cloud seeding in the respective regions.

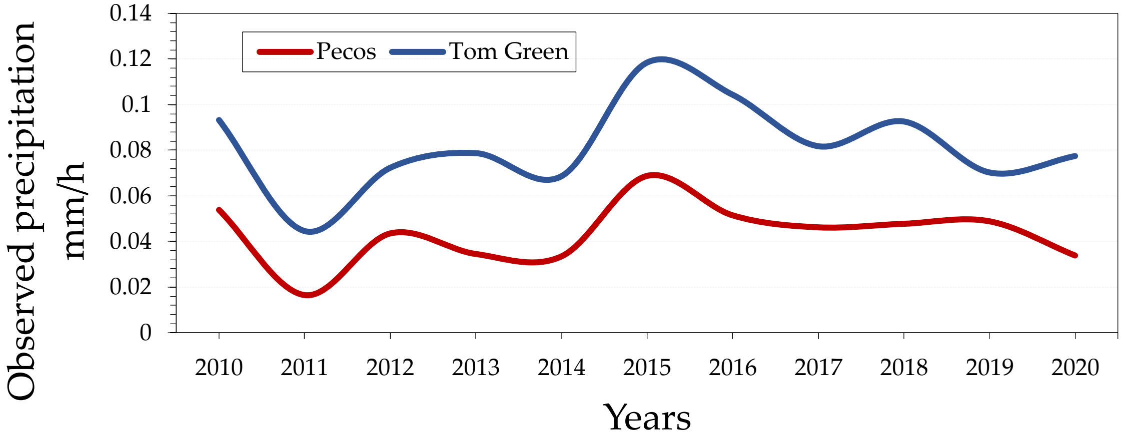


Figure 7. Comparison of the precipitation rate (mm/h) between Tom Green county and Pecos Counties, TX from 2010 to 2020 (no cloud seeding). These data was observed using GPM satellite.

Figure 7 shows that Tom Green County has a higher average precipitation compared to Pecos County even without seeding. The ratios between Tom Green and Pecos County precipitation rates are 0.49 and 0.55.

To investigate the relationship between rainfall precipitation and aerosols, we utilize data from the GPM instruments. The GPM mission provides global precipitation measurements with high spatio-temporal resolution. We focus on specific cloud seeding situations in San Angelo between 2015 and 2021 where cloud seeding operations were conducted. We extract area-averaged precipitation data from GPM for these specific cloud seeding events using Giovanni platform.

The collected precipitation data from GPM are analyzed to assess the relationship between rainfall and aerosols in cloud seeding situations. Statistical techniques, such as correlation analysis, are employed to quantify the degree of association between precipitation and aerosol levels. Additionally, box and whisker plots and time series analysis are used to examine the spatio-temporal patterns of precipitation and aerosols during cloud seeding events.

Below is the average precipitation levels in San Angelo in Texas (USA) btween 2015 and 2021.

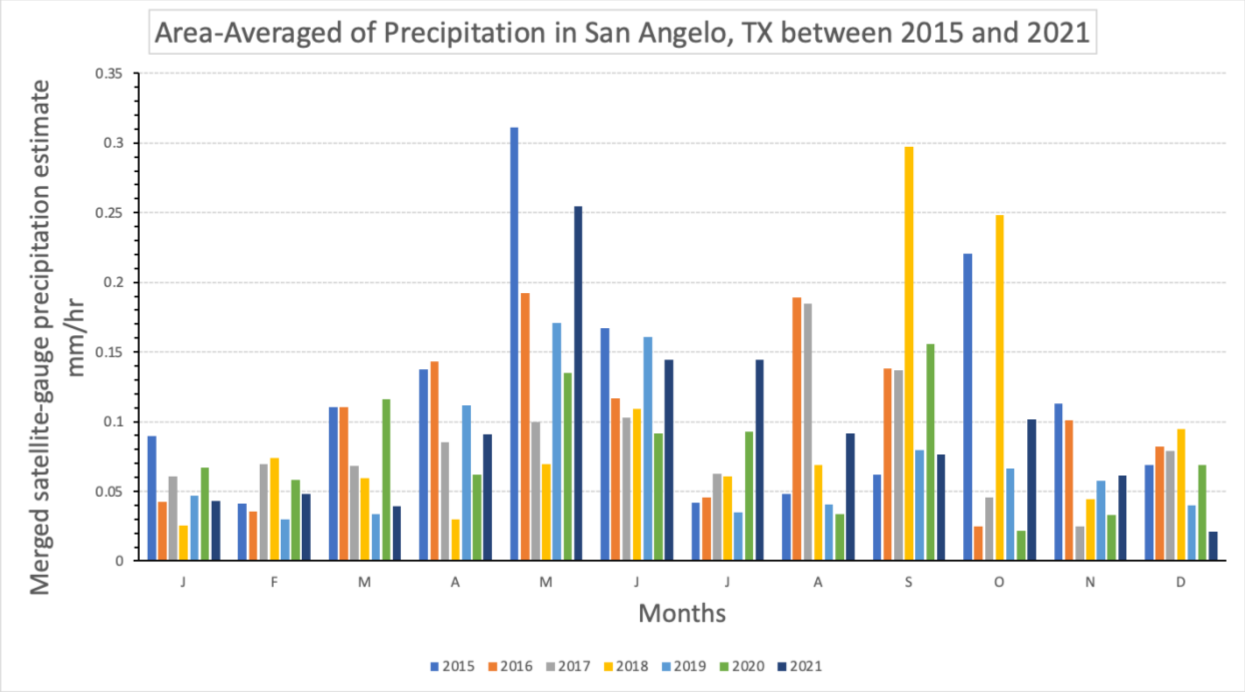


Figure 8. Time Series, Area-Averaged of Merged satellite-gauge precipitation estimate - Final Run, monthly in San Angelo, TX between 2015 and 2021.

CHAPTER 3: LONG-TERM STATISTICAL ANALYSIS.

1. Introduction

In this chapter, we delve into the comprehensive analysis of long-term data obtained from space-borne platforms such as MODIS (Moderate Resolution Imaging Spectroradiometer) and GPM (Global Precipitation Measurement) satellites. By examining aerosol optical depth (AOD), precipitation patterns, and Ångström Exponent (AE), we aim to understand the intricate relationship between cloud seeding activities and the dynamics of particulate matter. The investigation spans multiple geographical locations, including the United States, China, and the United Arab Emirates, offering a broad perspective on the environmental implications of cloud seeding. Through the lens of satellite-derived data, we unravel the complex interplay between aerosols, precipitation, and atmospheric conditions, shedding light on the potential impact of cloud seeding on air quality and particulate matter dynamics.

1.1 Comprehensive Review of Terra/Aqua-MODIS for Earth Observation

Earth observation satellites play a crucial role in providing valuable data for monitoring and analyzing the Earth's surface and atmosphere. Among these satellites, Terra and Aqua, launched by NASA in 1999 and 2002, respectively, have been instrumental in advancing our understanding of various environmental phenomena[43]. Equipped with the Moderate Resolution Imaging Spectroradiometer MODIS instrument, these satellites offer a wealth of data that have revolutionized the field of Earth observation. The MODIS instrument onboard Terra and Aqua satellites captures images in 36 spectral bands, ranging from visible to thermal infrared. These images provide valuable information on land, ocean, and atmospheric parameters at moderate spatial resolutions (250m to 1km) with daily global coverage[43]. The comprehensive spectral coverage and high temporal resolution make Terra/Aqua-MODIS a highly valuable tool for monitoring and analyzing Earth's dynamic processes. MODIS utilizes two key algorithms for aerosol retrieval: the Dark Target and Deep Blue algorithms. The Dark Target algorithm is designed to estimate aerosol optical depth over dark surfaces like oceans and forests, where aerosol concentration is relatively low. On the other hand, the Deep Blue algorithm focuses on estimating aerosol properties over brighter surfaces such as deserts and snow-covered areas, where aerosol loading tends to be higher compared to dark surfaces.

1.1.1. Applications of Terra/Aqua-MODIS

Terra/Aqua-MODIS data have been extensively utilized to monitor climate change indicators such as land surface temperature, sea surface temperature, cloud cover, and atmospheric aerosols. These data enable the assessment of long-term trends and anomalies, contributing to a better understanding of climate dynamics and informing climate change mitigation and adaptation strategies[43]. The multispectral capabilities of Terra/Aqua-MODIS facilitate accurate land cover mapping and land cover change detection. The data enable the identification and monitoring of various land cover types, including forests, croplands, urban areas, and water bodies. This information is vital for land management, biodiversity assessment, and urban planning[43].Terra/Aqua-MODIS data provide valuable insights into vegetation dynamics, including vegetation indices, leaf area index, and vegetation phenology. These parameters are vital for monitoring ecosystem health, assessing vegetation productivity, and detecting vegetation stress caused by factors such as drought, fire, or deforestation[36]. MODIS data, particularly the Aerosol Optical Depth (AOD) measurements, contribute significantly to air quality monitoring and assessment. The AOD data, combined with other atmospheric parameters, enable the identification and tracking of air pollutants, including dust, smoke, and industrial emissions. Such information aids in understanding air pollution patterns, assessing their impacts on human health, and guiding air quality management strategies[43].

1.1.2. Advantages and Limitations of Terra/Aqua-MODIS

Terra/Aqua-MODIS offers several advantages, including global coverage, regular revisit times, and a wide range of spectral bands. These advantages facilitate the monitoring of large-scale environmental processes, enabling researchers and policymakers to make informed decisions. However, limitations such as spatial resolution, cloud cover interference, and data processing challenges should be considered when utilizing Terra/Aqua-MODIS data[43]. Terra/Aqua-MODIS data have significantly advanced our understanding of Earth's dynamic processes. The applications of Terra/Aqua-MODIS in climate change monitoring, land cover mapping, vegetation dynamics, and air quality monitoring have been demonstrated and extensively studied. Despite some limitations, the future prospects of Terra/Aqua-MODIS are promising, with ongoing advancements in satellite technology and data analysis techniques. Harnessing the full potential of Terra/Aqua-MODIS will enable us to tackle pressing environmental challenges and contribute to sustainable development[43].

1.2. The concept of Ångström exponent

The Ångström exponent, also known as the Ångström turbidity coefficient, is a parameter used in atmospheric science to describe the size distribution of aerosol particles[44]. It is denoted by the symbol "α" and is derived from measurements of the attenuation of light at different wavelengths as it passes through the atmosphere. The Ångström exponent is related to the size of aerosol particles through their ability to scatter and absorb solar radiation[44]. When α is high, it indicates a dominance of small aerosol particles in the atmosphere, typically less than 0.1 micrometers in diameter. These particles are often associated with combustion byproducts, such as smoke and exhaust emissions. On the other hand, a low Ångström exponent suggests the presence of larger aerosol particles, typically greater than 1 micrometer in diameter. These particles are often associated with natural sources like sea spray, dust, or pollen[44]. The Ångström exponent provides valuable information about the properties and behavior of aerosols in the atmosphere. A high α value indicates a higher scattering efficiency of light, leading to increased atmospheric haziness. This can result in reduced visibility and the formation of haze or smog, which can have negative impacts on air quality and human health. Conversely, a low α value suggests that the aerosol particles are more efficient at absorbing sunlight. This absorption can contribute to localized heating effects and alter the temperature profile of the atmosphere[44]. It can also influence climate by affecting the radiative balance of the Earth's surface.

2. Statistical analysis in San Angelo, TX

2.1 Aerosols optical depth analysis in San Angelo TX

2.1.1. Introduction ana analysis.

Aerosol Optical Depth (AOD) is a vital parameter in atmospheric science, representing the amount of light absorbed or scattered by aerosol particles in the atmosphere[45]. Aerosol Optical

Depth (AOD) is a measure of how much light is absorbed or scattered by particles in the atmosphere. It quantifies the extinction of light due to aerosols as it passes through the atmosphere. In the context of cloud seeding, understanding the variation in AOD becomes crucial in identifying optimal conditions for effective weather modification. This study aims to compare the AOD levels in San Angelo in Texas (USA). To conduct this analysis, AOD data was collected and examined from the years 2015 to 2021 by GIOVANNI. The average AOD was calculated over this period. By comparing the average AOD values, the year with the higher AOD was identified. This information enabled to determine the month within the chosen year that exhibits the highest AOD, providing valuable insights for cloud seeding operations and related research. By examining the AOD levels, a comprehensive understanding of the atmospheric conditions that favor successful cloud seeding efforts. It is important to note that cloud seeding operations are carried out in diverse geographical regions, allowing comparison and contrast the AOD patterns across different climates and environmental conditions.

San Angelo area in Texas has been an active cloud seeding location since 2015[10]. The West Texas Weather Modification Association (WTWMA) has been conducting rain enhancement operations in this region, with regular reports and updates available on their official website. As an important aspect of studying the atmospheric conditions in the San Angelo area, the Aerosol Optical Depth (AOD) has been monitored between 2015 and 2021[41]. AOD is a measure of the amount of aerosols present in the atmosphere, and it provides insights into the air quality and the impact of aerosols on various environmental processes[45]. This study focuses on analyzing the AOD data during this period to assess the presence of aerosols in the atmosphere and any potential seasonal variations. Particularly, the analysis reveals that the AOD tends to be higher during the summer months, indicating a potential increase in aerosol concentrations during this time, see figure 13. Understanding the variations in AOD is crucial for assessing the impact of aerosols on climate, air quality, and other environmental processes. By studying the AOD in the San Angelo area, we can gain insights into the spatial and temporal distribution of aerosols and their potential implications for weather modification efforts and the local environment. The goal is to contribute to the understanding of aerosol dynamics and their relationship with cloud seeding operations and meteorological conditions in the San Angelo area. By analyzing the AOD trends and patterns, we can further evaluate the effectiveness and potential environmental impacts of cloud seeding activities in this region. Overall, the goal is to provide an overview of the San Angelo area, highlights the active cloud seeding operations conducted by WTWMA, and introduces the significance of studying the AOD to assess aerosol presence and potential seasonal variations in the atmosphere.

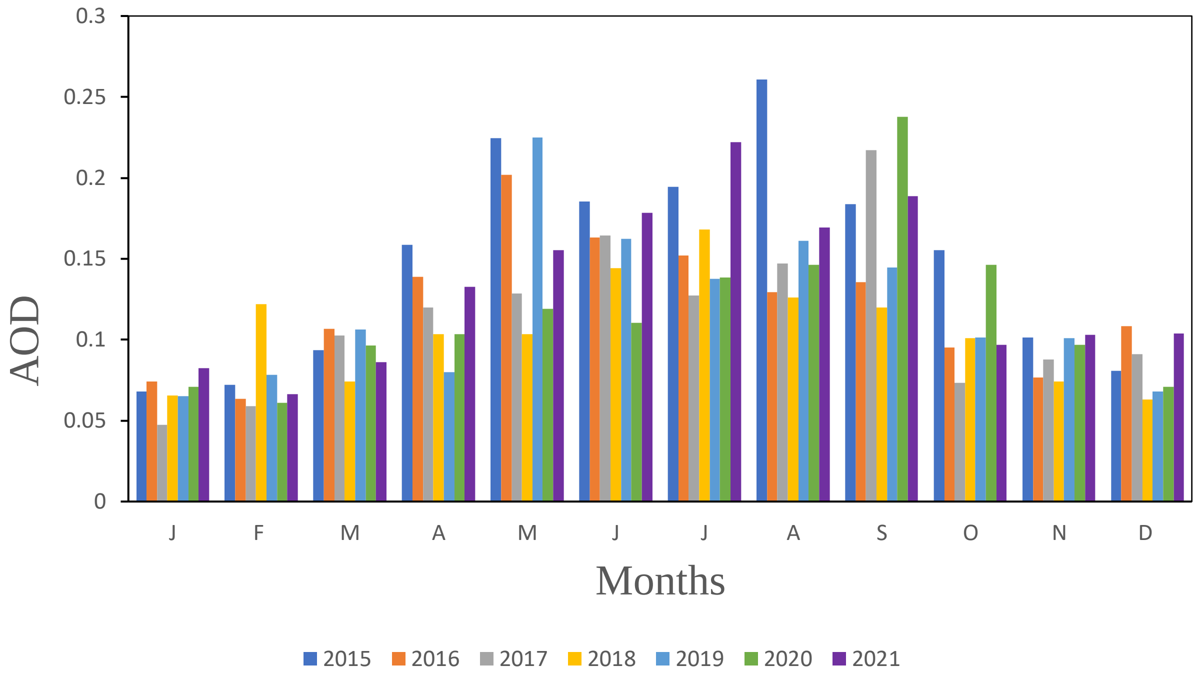


Figure 9. Time Series, Area-Averaged of Aerosol Optical Depth 550 nm (Dark Target) monthly in San Angelo, Texas between 2015 and 2021.

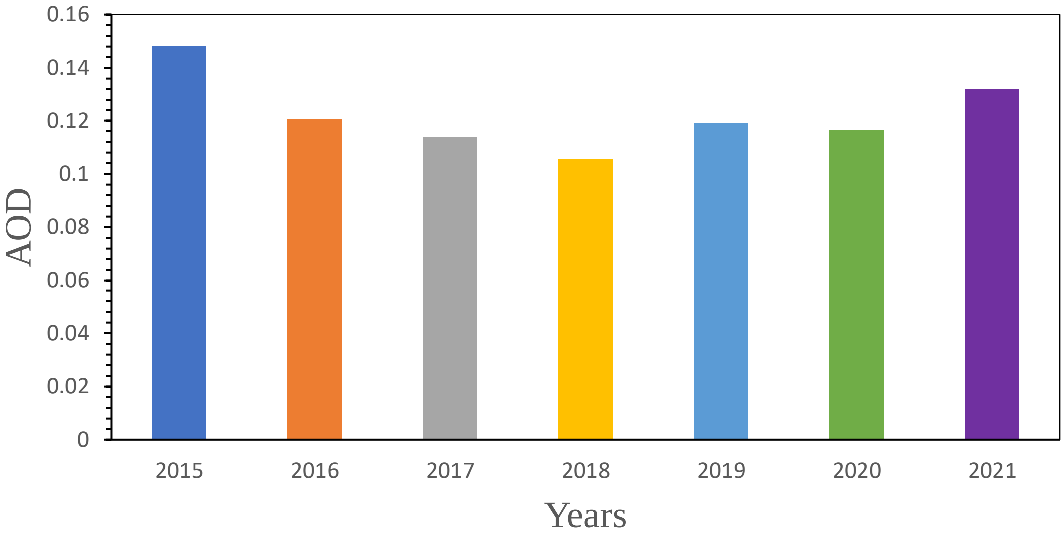


Figure 10. Annual average of Aerosol Optical Depth in San Angelo, Texas.

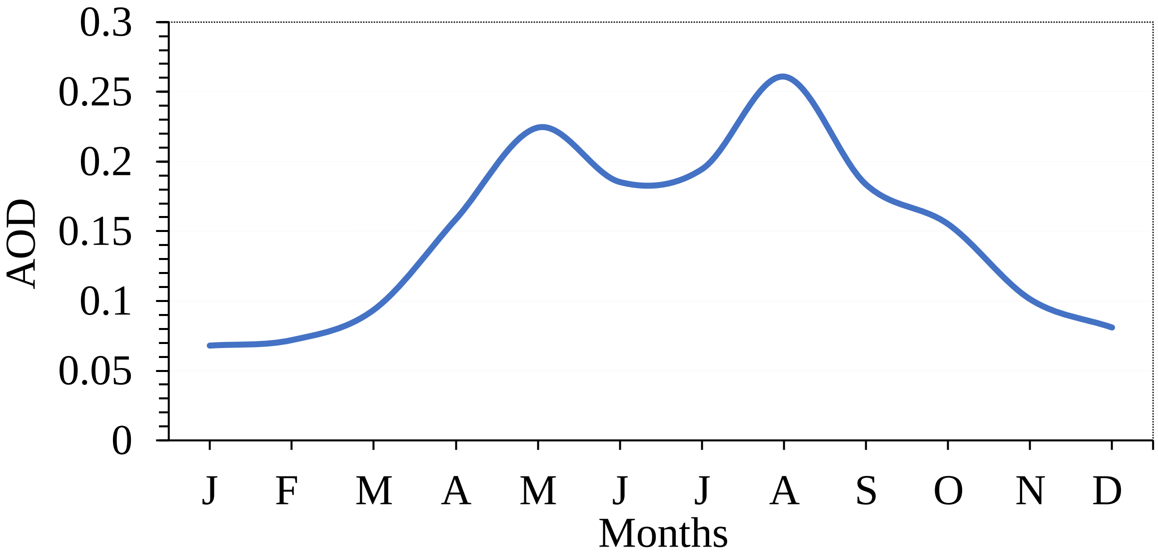


Figure 11. Time Series, Area-Averaged of Aerosol Optical Depth 550 nm (Dark Target) monthly in San Angelo, Texas (2015).

As sown in figure 14, 2015 has higher average AOD than other years, and the monthly AOD average is in its highest in August, see figure 15. To understand the situation more, daily AOD was plotted in the year of August. See figure 16.

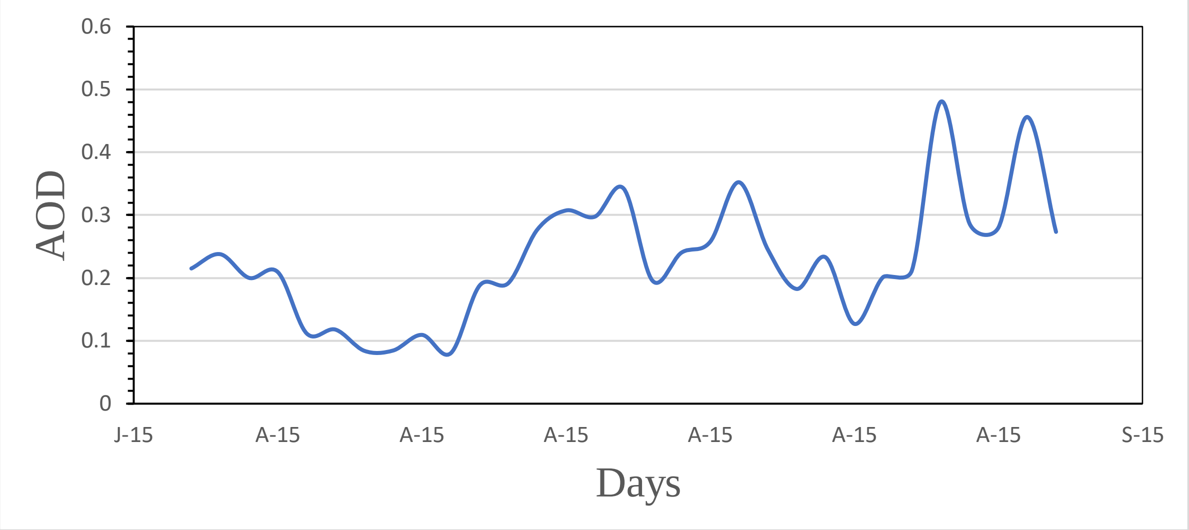


Figure 12. Time Series, Area-Averaged of Aerosol Optical Depth 550 nm (Dark Target) daily in San Angelo, Texas in August 2015.

The increase in Aerosol Optical Depth (AOD) can often be attributed to a variety of factors, and one noteworthy contributor is the rise in temperature[45]. As temperatures climb, the atmosphere becomes more dynamic, and several processes come into play that can elevate AOD levels. Higher temperatures can intensify the thermal-driven circulation of air, leading to increased emissions from various sources, such as industrial facilities and vehicular traffic[45], therefor, higher temperature will decrease atmospheric stability. This heightened activity releases a greater quantity of aerosols and particulate matter into the air. Additionally, elevated temperatures can influence atmospheric stability and mixing, potentially trapping pollutants closer to the surface. Such conditions not only exacerbate local AOD but can also impact regional air quality and have broader implications for climate change[45]. Consequently, understanding the relationship between temperature increases and AOD is vital for assessing air quality and addressing the environmental challenges associated with a warming climate. The analysis of AOD data remains essential for addressing air quality, climate, and environmental concerns, underscoring the importance of ongoing efforts to enhance data collection and quality control methods.

2.1.2. Analyzing storm runoff and cloud seeding operations in San Angelo TX

In the realm of cloud seeding, a crucial aspect to consider is the analysis of storm runoff data in specific regions to understand the effectiveness of cloud seeding operations. One such area of interest is San Angelo, Texas. In this endeavor, Giovanni[41], a powerful data visualization and analysis tool developed by NASA, has played a pivotal role in generating comprehensive storm runoff data for San Angelo. This data comprises invaluable insights into the hydrological dynamics of the region, including rainfall patterns, runoff volume, and temporal trends. By leveraging this dataset, researchers and scientists can establish a strong foundation for comparing the impacts of cloud seeding activities with atmospheric data like Aerosol Optical Depth (AOD). This comparative analysis offers a promising avenue for advancing our understanding of the complex relationship between weather modification practices and their environmental outcomes, contributing to more informed decisions regarding cloud seeding operations in San Angelo and beyond. See figures (17-18).

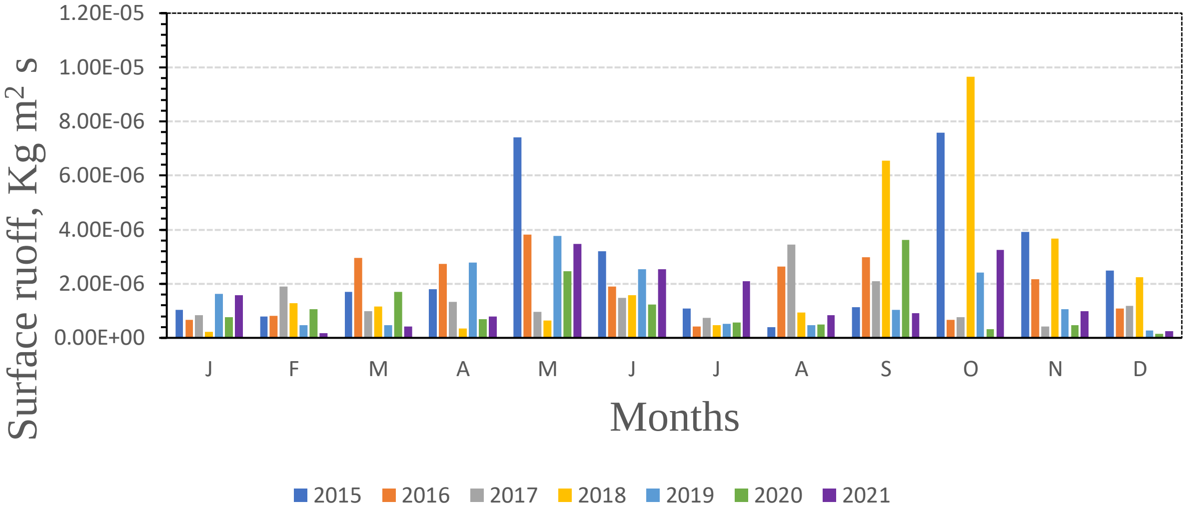


Figure 13. Time Series, Area-Averaged of Surface runoff monthly in San Angelo, Texas between 2015 and 2021.

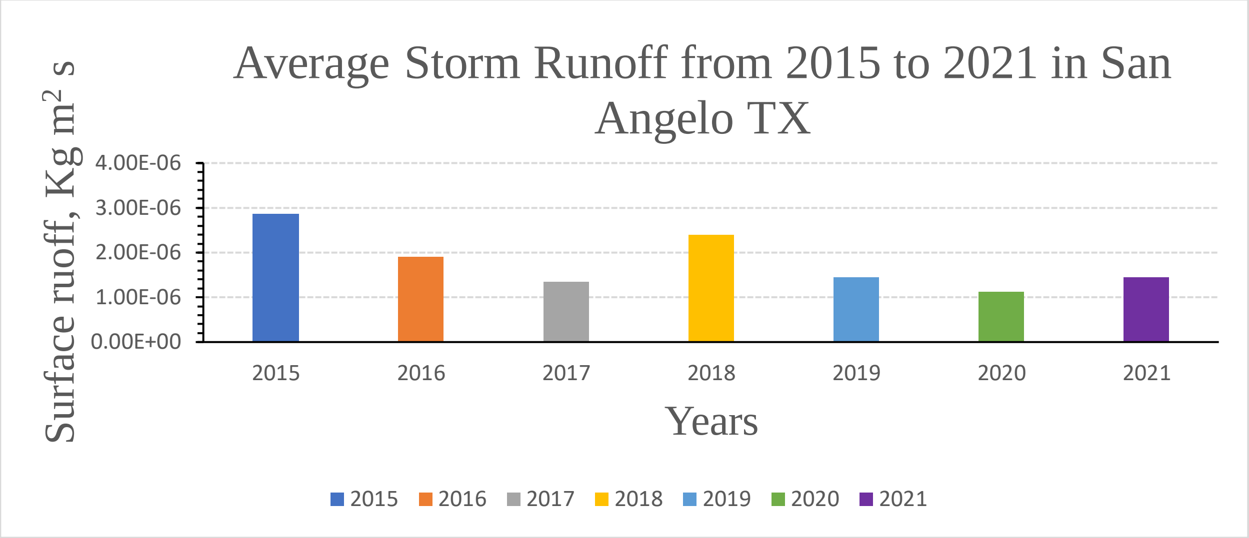


Figure 14. Annual average storm runoff in San Angelo, Texas (2015-2021).

Based on the annual reports total flares used in the operations were calculated for each year. See figure 19 and table 1.

Table 5. Annual amount of flares used during cloud seeding operations.

Year	AgI flares	Hygroscopic flares	Total flares
2015	1,410	117	1527
2016	1,184	94	1278
2017	959	51	1010
2018	730	38	768
2019	921	66	987
2020	759	89	848
2021	601	47	648

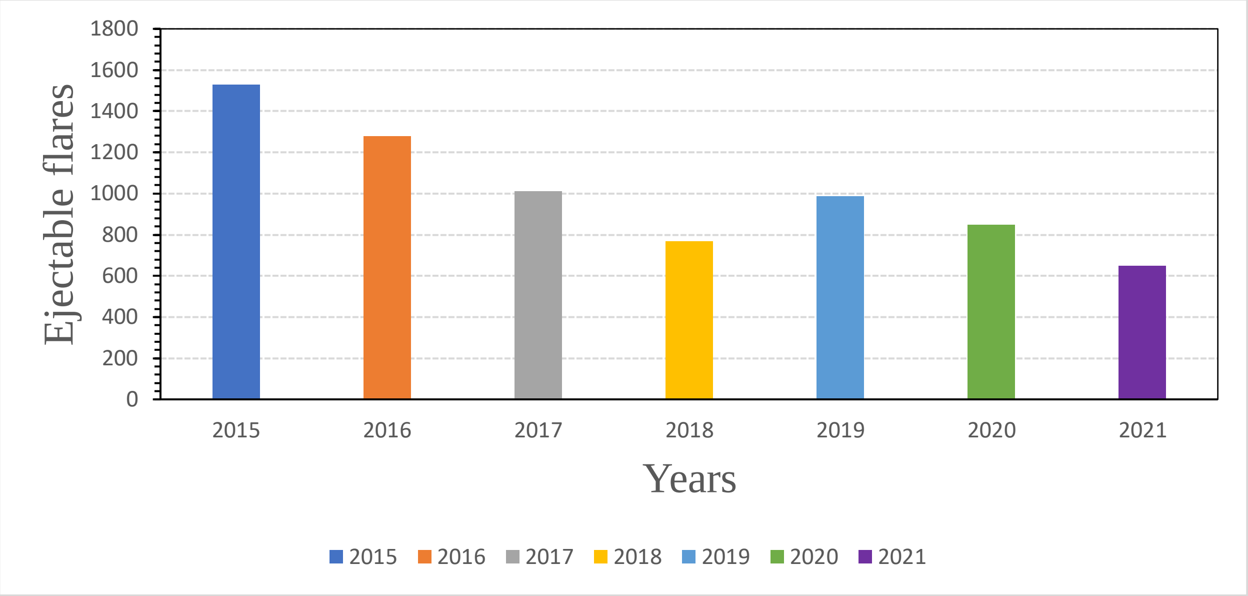


Figure 15. Total flares ejected in San Angelo TX (2015-2021).

2.1.3. Discussion

The Aerosol Optical Depth (AOD) is a measure of the amount of aerosols, such as dust, pollution, or natural particles, present in the atmosphere. During rainstorms, the AOD can exhibit complex behavior, and its response depends on various factors, including the type of aerosols, precipitation characteristics, and atmospheric conditions. While there isn't a straightforward relationship between rainstorms and changes in AOD, some studies have observed a decrease in AOD during rainfall events[45]. For example, Randles et al. (2017) analyzed satellite observations and found that AOD generally decreased during precipitation events over different regions worldwide. The study suggested that rain can scavenge and remove aerosols from the atmosphere, resulting in a temporary reduction in AOD. However, it is important to note that the behavior of AOD during rainstorms can vary depending on the specific aerosol types and meteorological conditions. Some studies have reported complex interactions between rain and aerosols, such as the formation of secondary aerosols due to chemical reactions occurring during rainfall.

Silver iodide (AgI) is sparingly soluble in water. It has a solubility of approximately 0.0000021 grams per liter at 25°C[46]. This limited solubility means that only a small amount of AgI dissolves in water, resulting in a low concentration of silver and iodide ions in solution. In the air, AgI can undergo reactions depending on environmental conditions[47]. It can act as a cloud condensation nuclei (CCN) and promote cloud formation. In the presence of moisture, AgI particles can nucleate ice crystals and facilitate the formation of ice clouds or precipitation[14]. This property is utilized in cloud seeding, where AgI particles are dispersed into clouds to enhance precipitation. Additionally, AgI can undergo photochemical reactions in the atmosphere due to its sensitivity to light. These reactions can lead to the production of other compounds, such as silver oxides or iodine species, depending on the specific environmental conditions[47]. It's important to note that the behavior of AgI in water and the atmosphere can vary depending on factors such as concentration, temperature, and other chemical interactions[46]. The presence of AgI (silver iodide) in the air can contribute to the aerosol population in the atmosphere. AgI particles themselves can act as aerosols, which are tiny solid or liquid particles suspended in the air. As AgI particles are dispersed into the air during cloud seeding, they become part of the aerosol mixture. The presence of these AgI particles contributes to the overall aerosol concentration in the atmosphere. It is important to note that the impact of AgI aerosols on the atmosphere and air quality depends on various factors, including the amount of AgI released, the dispersion patterns, and the regional environmental conditions.

The process of subsequent rainfall should wash aerosols, leading to an observed reduction in AOD. However, the data contradicted this hypothesis. The observation of an increase in Aerosol Optical Depth (AOD) at times when storm runoff is higher, seemingly contrary to what might be expected, invites a complex and intriguing discussion. One possible explanation for this phenomenon could indeed be the presence of silver iodide (AgI) in the atmosphere. As the data shows, when AgI presence is higher, AOD tends to be elevated as well.

The correlation between AgI and AOD could be attributed to several factors. First, the introduction of AgI particles into the atmosphere during cloud seeding may interact with existing aerosols and particles, potentially leading to complex chemical reactions. These reactions could result in the formation of additional aerosols or alterations in the composition of existing ones, causing an increase in AOD. Additionally, the role of meteorological conditions, including humidity and temperature, should be considered, as they can influence the behavior of aerosols in the atmosphere.

This intriguing relationship between AgI presence, storm runoff, and AOD highlights the intricate interactions within the atmosphere and underscores the need for comprehensive studies to decipher the underlying processes. Such insights are invaluable in advancing our knowledge of cloud seeding and its potential environmental consequences, as well as its broader implications for air quality and climate.

2.2. Ångström exponent analysis

Analyzing Ångström exponent data in San Angelo, TX is important because it can provide insights into the composition and size distribution of aerosol particles in the atmosphere. This data can help in understanding the effectiveness of cloud seeding, its impact on aerosol optical depth, and the levels of particulate matter in the air. By studying these factors, researchers can assess the environmental implications of cloud seeding activities and make informed decisions regarding its implementation. The data was collected using MODIS satellite provided by NASA[41]. See figures (20-23).

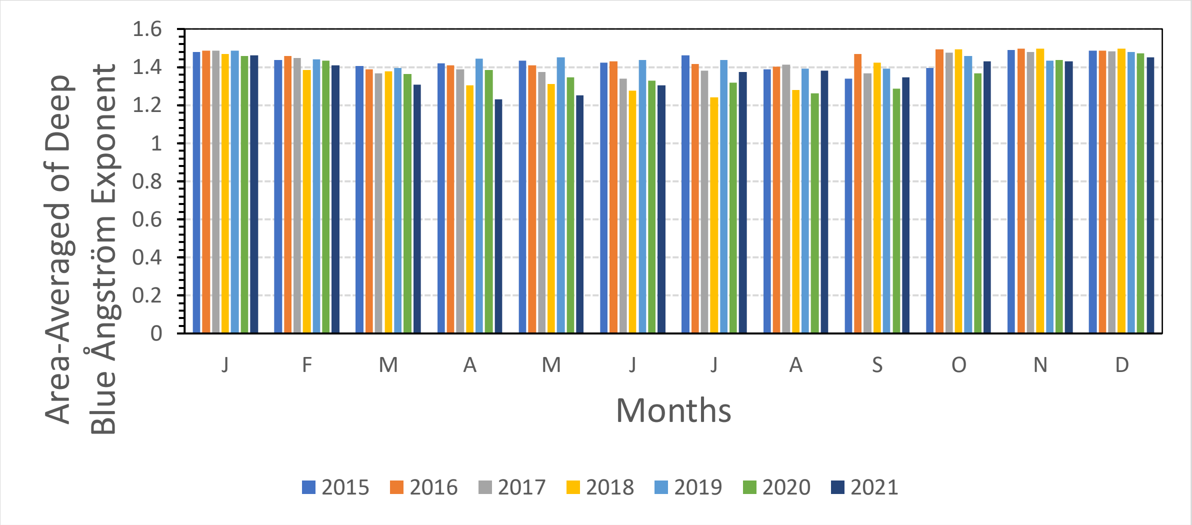


Figure 16. Area-Averaged of Ångström Exponent in San Angelo TX between 2015 and 2021.

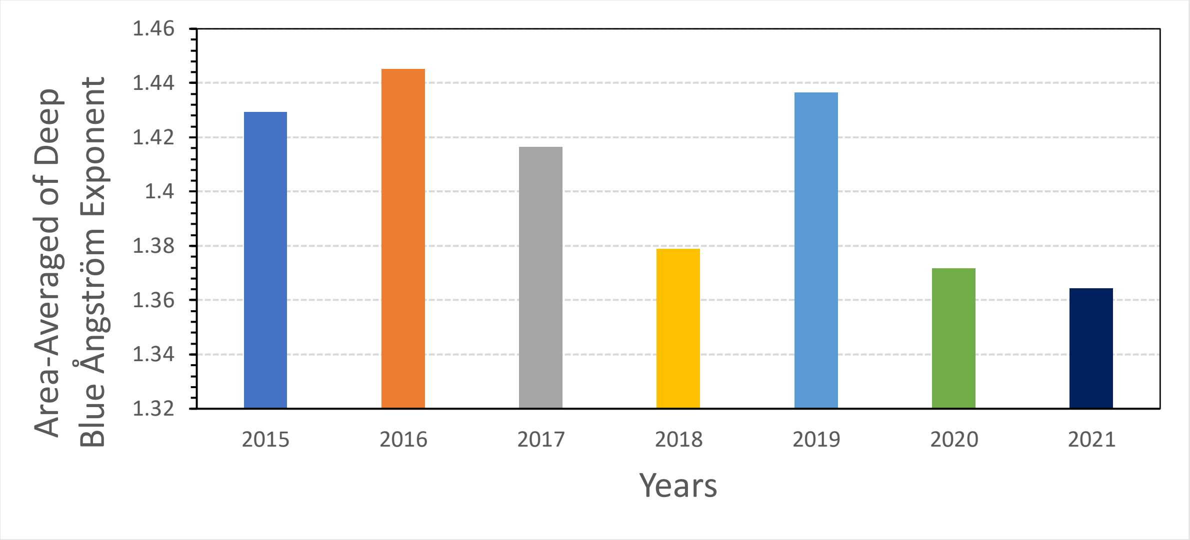


Figure 17. Area-Averaged of Ångström Exponent in San Angelo TX between 2015 and 2021.

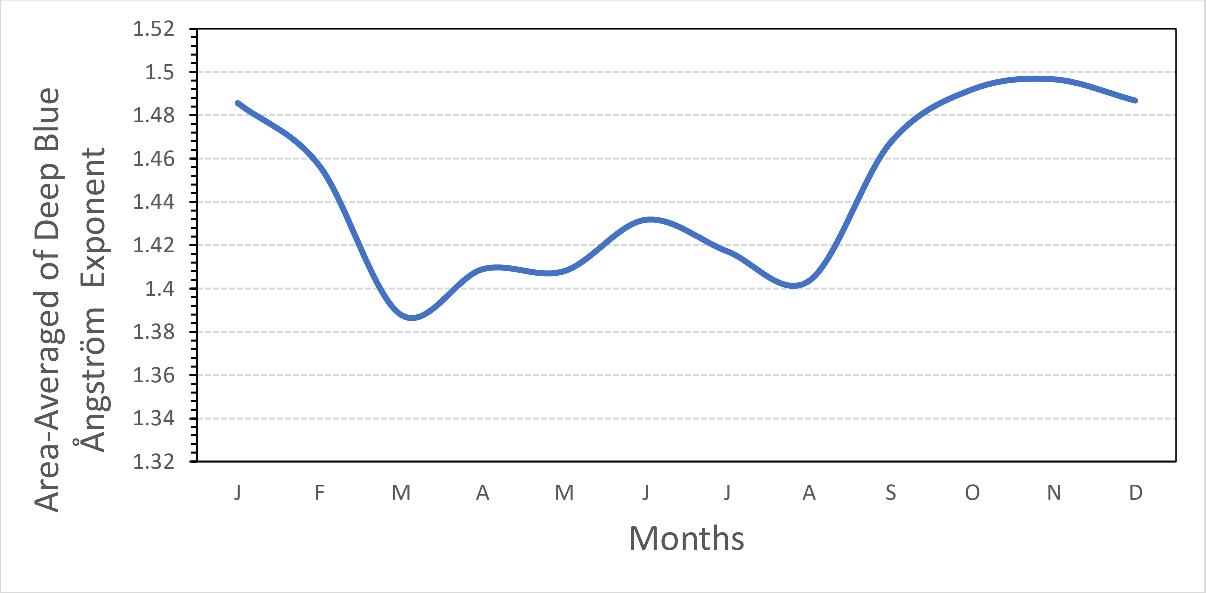


Figure 18. Area-Averaged of Ångström Exponent in San Angelo TX in 2016.

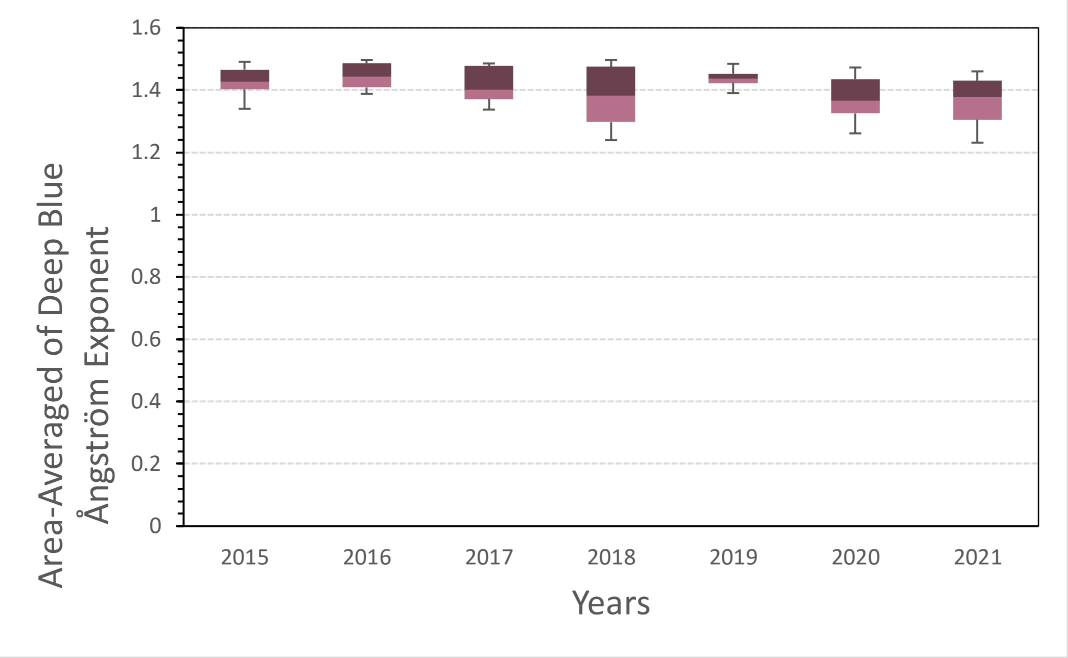


Figure 19. Box and whisker plot of Area-Averaged of Ångström Exponent in San Angelo TX (2015-2021).

Ångström exponent values are commonly used in atmospheric science to characterize the size distribution of aerosol particles in the atmosphere. The Ångström exponent is a parameter that describes the wavelength dependence of aerosol optical properties and can provide insights into the size of aerosol particles present in the air[44]. In relation to particulate matter size, specifically PM10 and PM2.5, Ångström exponent values can be indicative of the size distribution of these particles. PM10 refers to inhalable particles with diameters that are generally 10 micrometers and smaller, while PM2.5 refers to fine inhalable particles with diameters that are 2.5 micrometers and smaller[48]. The Ångström exponent can help researchers estimate the size range of aerosol particles contributing to the PM10 and PM2.5 fractions. Studies have shown that there is a relationship between Ångström exponent values and particle matter sizes such as PM10 and PM2.5[48]. A lower Ångström exponent value is often associated with the presence of larger particles, while a higher value may indicate the dominance of smaller particles in the aerosol size distribution. By analyzing the Ångström exponent alongside PM10 and PM2.5 data, researchers can gain a better understanding of the composition and size distribution of particulate matter in the atmosphere.

2.2.2. Relationship between precipitation of rain and aerosols:

Precipitation measurement plays a crucial role in understanding and studying the relationship between rain and aerosols in the atmosphere. When it comes to relating precipitation measurements to aerosol levels, it is essential to combine precipitation data with aerosol measurements from specialized instruments. The impact of precipitation levels on aerosol concentrations in the atmosphere is a subject of scientific interest due to its implications for understanding the complex interactions between water vapor, clouds, and aerosols[49].

Precipitation plays a crucial role in removing aerosol particles from the atmosphere through a process called wet deposition[49]. As raindrops or snowflakes form, they capture aerosol particles and carry them to the Earth's surface. This process effectively reduces aerosol concentrations in the atmosphere, leading to cleaner air. Precipitation also influences aerosol concentrations indirectly through processes such as scavenging and coagulation. Scavenging occurs when raindrops intercept and remove aerosol particles from the air. Coagulation refers to the collision and merging of aerosol particles with raindrops, leading to a change in their size distribution. Both processes can affect the number and size distribution of aerosols in the atmosphere[40]. Intense precipitation events can result in a phenomenon known as precipitation-induced washout. This occurs when raindrops falling through the atmosphere entrain and scavenge aerosol particles, effectively cleansing the air. These washout events can lead to temporary reductions in aerosol concentrations, which can have implications for local air quality and climate[50].

It is important to note that the relationship between precipitation and aerosol levels is not always straightforward. Various factors, including atmospheric dynamics, geographical location, and meteorological conditions, can influence this relationship. Moreover, the complex nature of aerosol-cloud-precipitation interactions requires detailed observational and modeling studies to better understand the mechanisms at play. But we can say in principle that rain precipitation is supposed to reduce aerosols in natural situations, based on previous studies.

The correlation between precipitation and aerosols optical depth in San Angelo (in 2015 when cloud seeding operations started and 2011 before any attempt of cloud seeding):

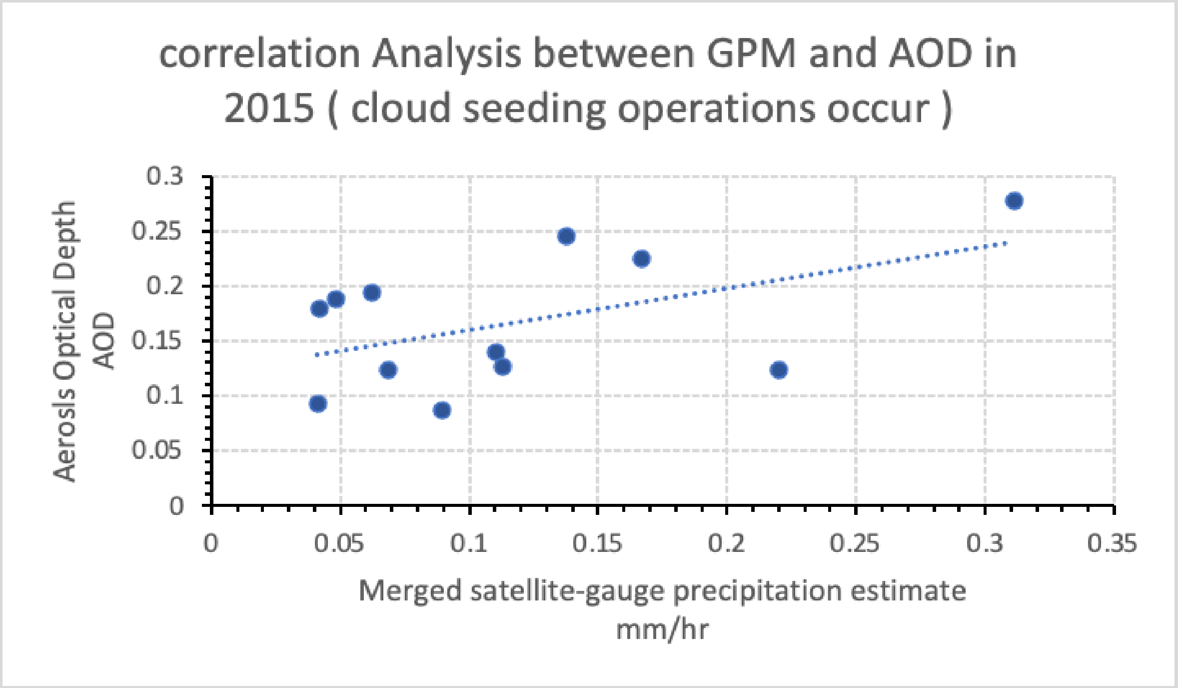


Figure 20. The correlation between precipitation and aerosols optical depth in San Angelo in seeding time.

Correlation value = 0.50816871

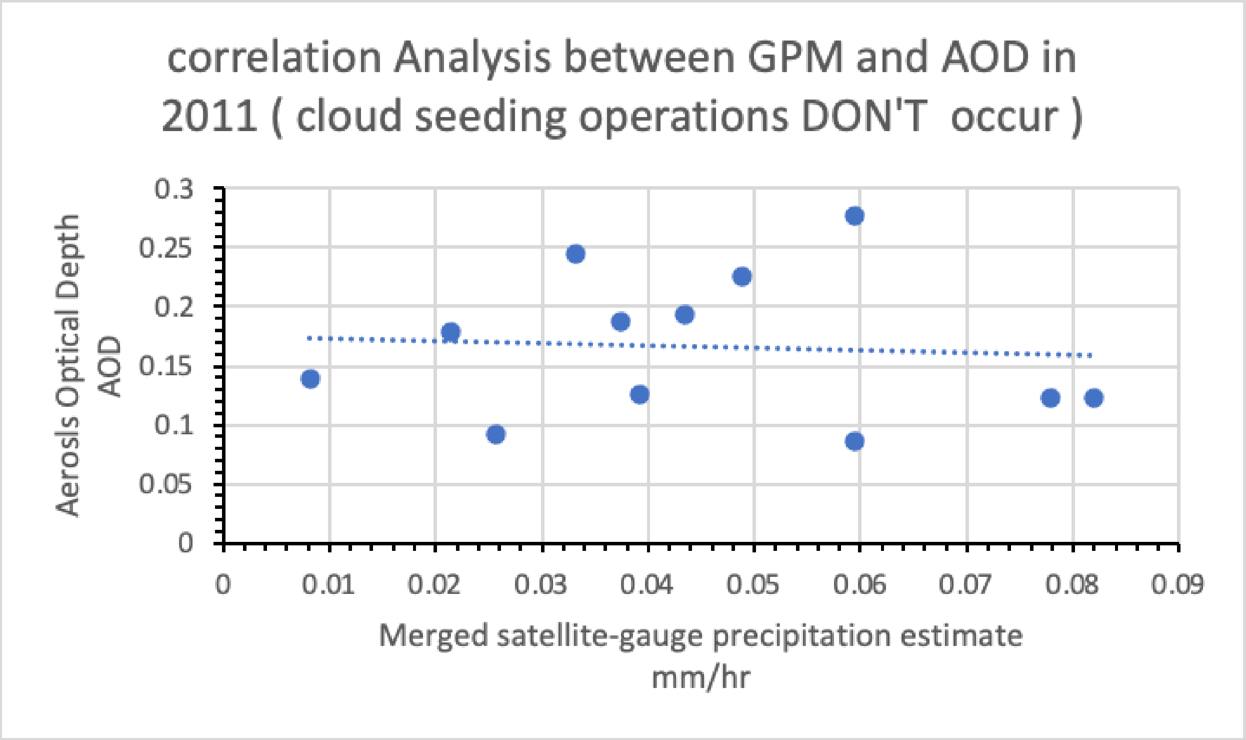


Figure 21. The correlation between precipitation and aerosols optical depth in San Angelo before seeding time.

Correlation value = -0.0755305

In Figures 20 and 21, it is important to note that the slopes may not be directly comparable due to the absence of substantial precipitation events in the initial years of the decade. These figures highlight the correlation between precipitation and Aerosol Optical Depth (AOD) before and after seeding. The correlation values of -0.0755 in the no-seeding scenario and 0.5081 in the seeding scenario suggest a lack of statistical significance in the relationship between precipitation and AOD in both scenarios.

2.2.3. Discussion.

In this study, we investigated the relationship between rainfall precipitation and aerosols in cloud seeding situations, focusing on specific locations known for cloud seeding operations between 2015 and 2021. While our analysis provided valuable insights into the relationship between precipitation and aerosols in San Angelo, Texas, it is important to note that data availability limited our ability to draw conclusions for other locations.

For San Angelo, Texas, the analysis revealed interesting findings. In 2015, when cloud seeding operations were conducted, we observed a positive correlation between precipitation and aerosol optical depth (AOD) (Correlation value = 0.50816871). This positive correlation suggests that cloud seeding may have played a role in enhancing precipitation in San Angelo during that period. The introduction of additional particles through cloud seeding may have influenced cloud microphysics, leading to increased cloud droplet formation and subsequent rainfall. Hence, the precipitation of rain is not washing aerosols away. This means that a large portion of silver iodide remains in the atmospheric layers in the form of aerosols, as it does not combine with water droplets and is not washed away by rain from the atmosphere. This means that a large portion of AgI remains in the atmospheric layers in the form of aerosols, as it does not combine with water droplets and is not washed away by rain from the atmosphere.

On the other hand, in 2011, before the implementation of cloud seeding operations, we observed a weak negative correlation between precipitation and AOD (Correlation value = -0.0755305). This finding indicates that natural atmospheric processes governed the precipitation patterns during that time, with aerosols potentially playing a minor role in precipitation formation.

Further research is necessary to encompass a wider range of cloud seeding locations and time periods, with comprehensive data access. Long-term studies that include multiple cloud seeding events, along with detailed measurements of aerosol properties, cloud microphysics, and precipitation processes, are crucial for a more comprehensive understanding of the relationship between cloud seeding, precipitation, and aerosols.

Additionally, it is important to consider other factors that can influence the relationship between precipitation and aerosols, such as meteorological conditions, geographical characteristics, and the specific techniques employed in cloud seeding operations. These factors can significantly impact the effectiveness of cloud seeding in enhancing precipitation and the influence of aerosols on cloud processes.

In conclusion, while our analysis for San Angelo, Texas indicates a positive correlation between precipitation and aerosols during cloud seeding events, further research is needed to draw definitive conclusions.

2.2.4. Conclusion.

This study contributes to the understanding of the relationship between rainfall precipitation and aerosols in cloud seeding situations. The analysis of GPM precipitation data and MODIS aerosol measurements provides insights into the potential impact of cloud seeding on precipitation and aerosol levels. The results highlight the complex interactions between cloud physics, rainfall, and aerosols. The data were collected from GPM and MODIS indicate the enhancement of precipitation in cloud seeding operation in San Angelo. In the other hand, it is indicating that aerosols concentration remains high in the atmosphere on these days of seeding operations.

2.3. Analysis of aerosols and Ångström exponent in San Angelo TX during last season of seeding (2023).

The introduction of cloud seeding agents into the atmosphere has long been proposed as a method to enhance precipitation and mitigate the effects of drought. However, the impact of such interventions on atmospheric properties, including aerosol optical depth (AOD) and the Ångström exponent (AE), remains a subject of scientific inquiry. AOD measures the extinction of solar radiation by aerosol particles in the atmosphere, while AE is related to the particle size distribution of aerosols, with lower values indicating larger particles. This study aims to analyze the variations in AOD and AE during cloud seeding operations over a period in 2023, providing insights into the immediate atmospheric consequences of seeding activities.

The study was conducted over a 22-day period in 2023, during which cloud seeding operations were carried out. Atmospheric data were collected using satellite observations and ground-based monitoring stations to record AOD and AE values. The analysis focused on comparing the AOD and AE values on the days of seeding operations with those from the previous days. This approach allowed for the assessment of immediate changes in atmospheric aerosol properties attributable to cloud seeding. The study also monitored the return of AE and AOD levels to baseline values following seeding activities to evaluate the persistence of any observed changes.

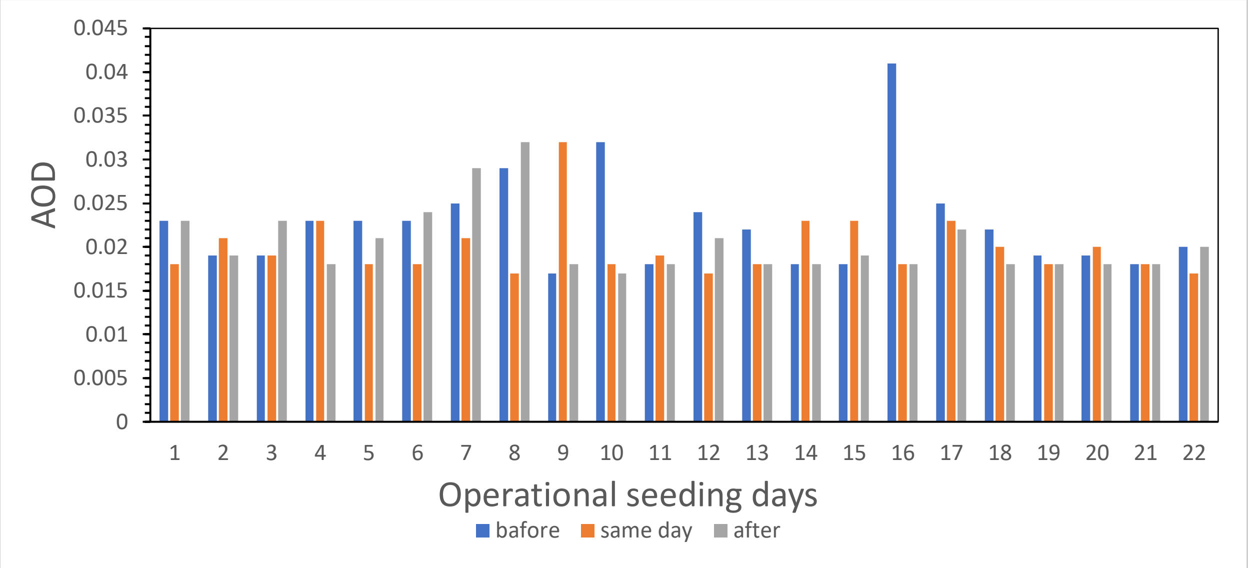


Figure 22. Ångström Exponent in seeding days in San Angelo TX (2023).

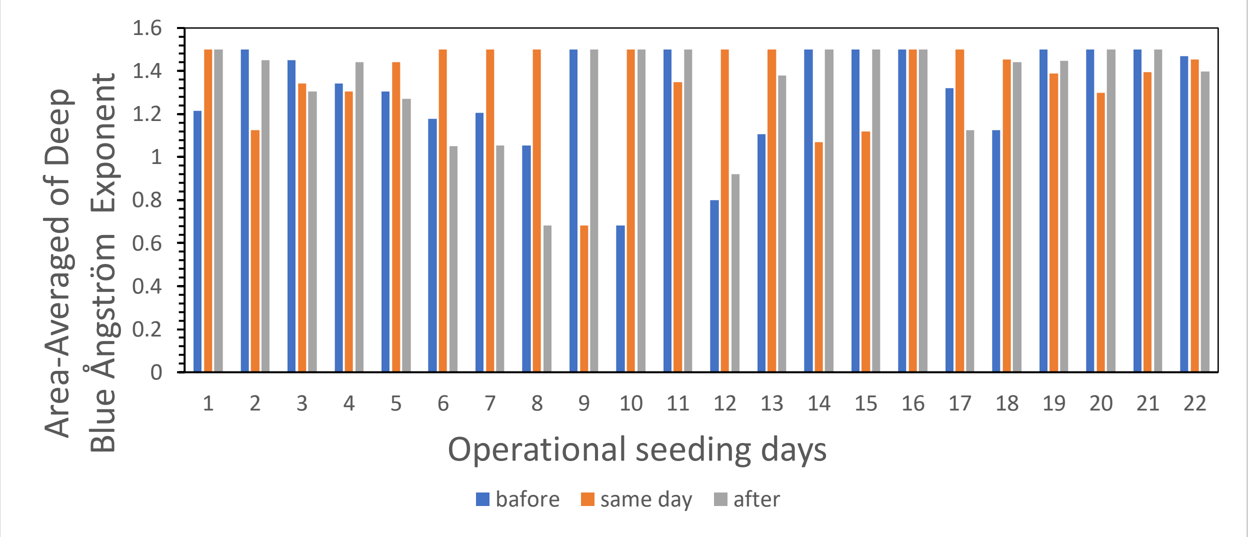


Figure 23. Ångström Exponent in seeding days in San Angelo TX (2023).

The analysis revealed that on 6 out of 22 seeding days, AOD values were higher on the day of seeding compared to the previous day, suggesting an increase in aerosol particles following seeding operations. This increase could be attributed to the introduction of seeding agents such as silver iodide (AgI) into the atmosphere, which may contribute to aerosol loading. Conversely, AE values decreased on 11 out of 22 seeding days, indicating a shift towards larger aerosol particles on these days. This change in AE could be related to the aggregation of smaller aerosol particles around seeding agents, leading to the formation of larger particles. The observed return of AE and AOD levels to their normal values after the seeding day suggests that the impact of cloud seeding on atmospheric aerosol properties is transient. This temporary nature of the changes indicates that cloud seeding, as performed during the study period, does not result in long-term alterations of aerosol optical properties in the atmosphere. The findings highlight the complexity of the interactions between cloud seeding operations and atmospheric aerosols. While the study provides evidence of immediate, transient changes in AOD and AE following cloud seeding, the environmental implications of these changes remain to be fully understood. Further research is needed to explore the long-term impacts of cloud seeding on atmospheric composition, cloud formation processes, and weather patterns, considering the varying conditions under which seeding is performed and the different seeding agents used.

3. Review on Cloud Seeding Impact on Air Quality and Particulate Matter Dynamics: Case Study from United Arab Emirates

This review delves into the intricate relationship between cloud seeding activities and the levels of particle matters, specifically PM10 and PM2.5, in the context of air pollution. By examining existing literature and studies, this review aims to explore the impacts, correlations, and implications of cloud seeding on the concentration and distribution of these particles in the atmosphere.

A study[51] analyzed the impact of cloud seeding missions on air quality in the UAE. The research used satellite data and air quality monitoring stations to evaluate the influence of cloud seeding missions conducted from January to March 2017. It focused on particulate matter (PM) variability during and after the cloud seeding missions, particularly PM10 and PM2.5 concentrations, and their correlation with aerosol optical depth. The findings indicated that cloud seeding missions might have increased the concentration of PM in the air, with a more significant effect on PM10 concentrations compared with PM2.5. Furthermore, the research investigated the environmental effects of cloud seeding on fine and coarse PM loading in the UAE in 2017. The data analysis from ground-based air quality monitoring stations showed an increase in PM concentrations during and after the cloud seeding missions. Another study shows the results reveal a decrease in PM10 concentration in the areas affected by cloud seeding, indicating the potential effectiveness of reducing fine dust concentration in the atmosphere through cloud seeding.

The aerosol optical depth (AOD) trend in the UAE in 2017 varied with seasonal changes. The study analyzed the AOD trends based on the MAIAC 1-km data and found that lower aerosol loadings were observed during winter and spring compared to summer and fall[51,52]. Higher AOD values were observed during summer, attributed to the lack of precipitation and dry soil contributing to higher aerosol loadings in the atmosphere. This was further influenced by high summer temperatures and relative humidity, resulting in increased anthropogenic aerosol loadings due to the primary energy source in the UAE being fossil fuel. In contrast, lower AOD values were observed in winter and fall, attributed to the reduction in dust loading into the atmosphere during these seasons. Additionally, the study showed that the 2017 cloud seeding project increased precipitation rates from February to March, contributing to low AOD during the spring of 2017 as raindrops washed out aerosol particles in the atmosphere. The experiments were conducted in west Korea along the Yellow Sea coast, numerical simulations showed the diffusion of the seeding material in specific areas, along with the enhanced radar reflectivity and increased concentration of cloud, drizzle, and precipitation particles after seeding. The findings suggest the possibility of reducing fine dust concentration in the atmosphere through cloud seeding[52]. While the analysis of data from 20 air quality monitoring stations in United Arab Emerits revealed a substantial increase in PM10 concentrations during the cloud seeding missions compared to the months thereafter. This increase in PM10 concentrations was attributed to the silver iodine crystals fired into the clouds during the missions, which degraded into smaller particles, forming PMs of different sizes that remained suspended in the atmosphere. Additionally, the research highlighted that local weather conditions during the cloud seeding missions could have contributed to the degradation of silver iodine crystals, resulting in a higher chance of coarse particle formation[51].

A study reveals that certain gaseous pollutants and PM10 exhibit a significant negative correlation with rainfall, possibly due to temperature inversion preventing the upward rise of humid air and convective clouds. Surprisingly, PM2.5 shows a positive significant effect on rainfall. The findings support the hypothesis of rain prevention by pollutants but also suggest nuances dependent on the size of air particle matters, highlighting the need for emission purification technologies to achieve environmental sustainability while promoting economic growth[53]. The results indicate a negative correlation between certain pollutants (CO, SO2, NO, and PM10) and rainfall occurrence, while PM2.5 shows a positive relationship with rain occurrence. The document emphasizes the role of particulate matters as cloud condensation nuclei, influencing cloud droplet formation and the subsequent suppression of precipitation. The study suggests that air pollutants, particularly particulate matters, play a role in cloud condensation nuclei (CCN), attracting cloud droplets by adsorption. However, the presence of smaller cloud droplets due to elevated air pollution concentrations can suppress precipitation formation, leading to a longer cloud lifetime and a reduction in precipitation occurrence. The findings also suggest that the ground for cloud seeding to provoke rainfall may exist, but poor air quality driven by dust and gaseous pollutants generated by industrial activities is a public health concern that needs to be addressed[53]. Cloud seeding missions had a significant impact on increasing fine particulate matter (PM2.5) concentrations in the atmosphere. Specifically, the study observed high concentrations of fine particles during the cloud seeding missions. This indicated the environmental impact of cloud seeding in loading fine particulates in the atmosphere and the possible degradation of silver iodine crystals used in cloud seeding into fine particles[51]. Despite the results of the cloud seeding experiments for reducing fine dust concentration showed that the seeding material diffused in specific areas, leading to enhanced radar reflectivity and increased concentration of cloud, drizzle, and precipitation particles after seeding. The analysis of numerical simulation data, ground, and aircraft observation data indicated a decrease in PM10 concentration during the effective time of the cloud seeding material, suggesting the potential for reducing fine dust using this technique[52]. Overall, Pollutants may prevent or reduce rainfall, with some nuances in the relationship between different pollutants and rainfall occurrence and quantity[53]. It is important to consider the potential environmental impacts of cloud seeding, including the injection of chemicals into the atmosphere and the subsequent increase in PM concentrations, which could have implications for air quality and human health[51].

4. Review on Cloud Seeding Impact on Air Quality and Particulate Matter Dynamics in China.

China has been actively involved in cloud seeding operations to enhance precipitation, particularly in regions facing water scarcity. The impact of cloud seeding on air quality and particulate matter in China is a complex topic. While cloud seeding aims to increase precipitation, potentially reducing air pollution by removing particles from the atmosphere through rainout, there are also concerns about the introduction of additional particles into the air through the seeding process. Several studies have examined the effects of cloud seeding on air quality and particulate matter in China. Some research indicates that cloud seeding can have both positive and negative impacts on air quality, depending on factors such as seeding methods, meteorological conditions, and the type of aerosols used for seeding. One study investigated the impact of cloud seeding on aerosol concentrations and air quality in Beijing, China[54]. The study found that cloud seeding led to changes in aerosol properties and concentrations, affecting air quality in the region. Another study analyzed the influence of cloud seeding activities on particulate matter levels in a specific region of China[55]. The study highlighted the importance of considering the environmental consequences of cloud seeding on air quality and particulate matter concentrations.

CHAPTER 4. IMPACT OF CLOUD SEEDING ON HYDROLOGICAL PROCESSES.

1. Introduction

Assessing the effectiveness of cloud seeding and its impact on hydrological processes requires a comprehensive analysis using geographic information systems (GIS) tools. The objective of this project was to evaluate the impact of cloud seeding on hydrological processes within a selected watershed. Specifically, the study will investigate changes in runoff, and water availability using two widely used GIS platforms, Quantum Geographic Information System (QGIS)[56] and Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS)[57]. By examining the spatial patterns and temporal variations of these hydrological parameters, we aim to gain insights into the effectiveness of cloud seeding and its implications for water resource management.

The selected GIS platforms, QGIS and ArcGIS, offer powerful tools for spatial analysis and visualization. QGIS, an open-source software, provides an extensive range of geoprocessing capabilities and is widely used by researchers and practitioners. On the other hand, ArcGIS, a proprietary software developed by Esri[57], offers advanced functionality for spatial data analysis and modeling.

2. Methodology

The annual reports from West Texas Weather Modification Association[10] were analyzed to calculate the estimated precipitation before and after seeding in Tom Green County. Additionally, seeding days during the last season (2023) were identified based on available records on the precipitation graph derived from MODIS satellite daily data from GIOVANNI platform[41].

S Concho Rv at Christoval, TX gauge was selected as it is located in the seeding area[10]. The gauge provides information on the flow of the river. The primary constituents of the river are natural stream runoff and rain precepitation[58]. Daily discharge data from the USGS (the nation's largest mapping agency)[59] for the identified location as well as Concho Rv at Paint Rock, TX (gauge located outside seeding area) was obtained to compare them. The gauge measures water flow, which is primarily provided by the Concho River with the contribution of smaller tributaries[60].

To better understand the effect of cloud seeding on hydrological process, data of DEM (Digital Elevation Model), land cover, soil of South Concho River at Christoval, TX watershed area was collected to generate the stream runoff using QGIS. The curve number (a hydrologic parameter used to describe the stormwater runoff potential) obtained from processing the data in QGIS to examine how precipitation would affect the stream runoff using the following equation[61]):

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \qquad (1)$$

$$S = \frac{1000}{CN} - 10 \qquad (2)$$

Where Q = Runoff (additional water that land absorb) (In), P = Rain precipitation (In/hr), S = Potential maximum retention (infiltration occurring after the beginning of runoff) (In), and CN = Curve Number (hydrologic parameter used to describe the stormwater runoff potential)

The curve number method is used to estimate storm water runoff from a particular area based on its land use, soil type, and hydrological conditions. The equation takes into account the initial abstraction, which represents the amount of rainfall that is retained or lost before runoff begins. In this case, the equation assumes an initial abstraction of 0.2 times the potential maximum retention (S).

The potential maximum retention (S) represents the maximum amount of rainfall that can be retained by the soil before runoff occurs[61]. To calculate the storm runoff, the equation utilizes curve numbers obtained using QGIS software. These curve numbers are determined based on actual and expected precipitation data[10], along with information from the USGS database[59]. By applying the appropriate curve numbers and the calculated S value, the equation allows for the estimation of storm runoff from the given area[61].

3. Results

Furthermore, the S Concho River above Gardner Dam near San Angelo as the gate of the watershed within Tom Green County has been identified and obtained daily discharge data and gate height information (Figure 8) before the seeding period from the United States Geological Survey (USGS)[59].

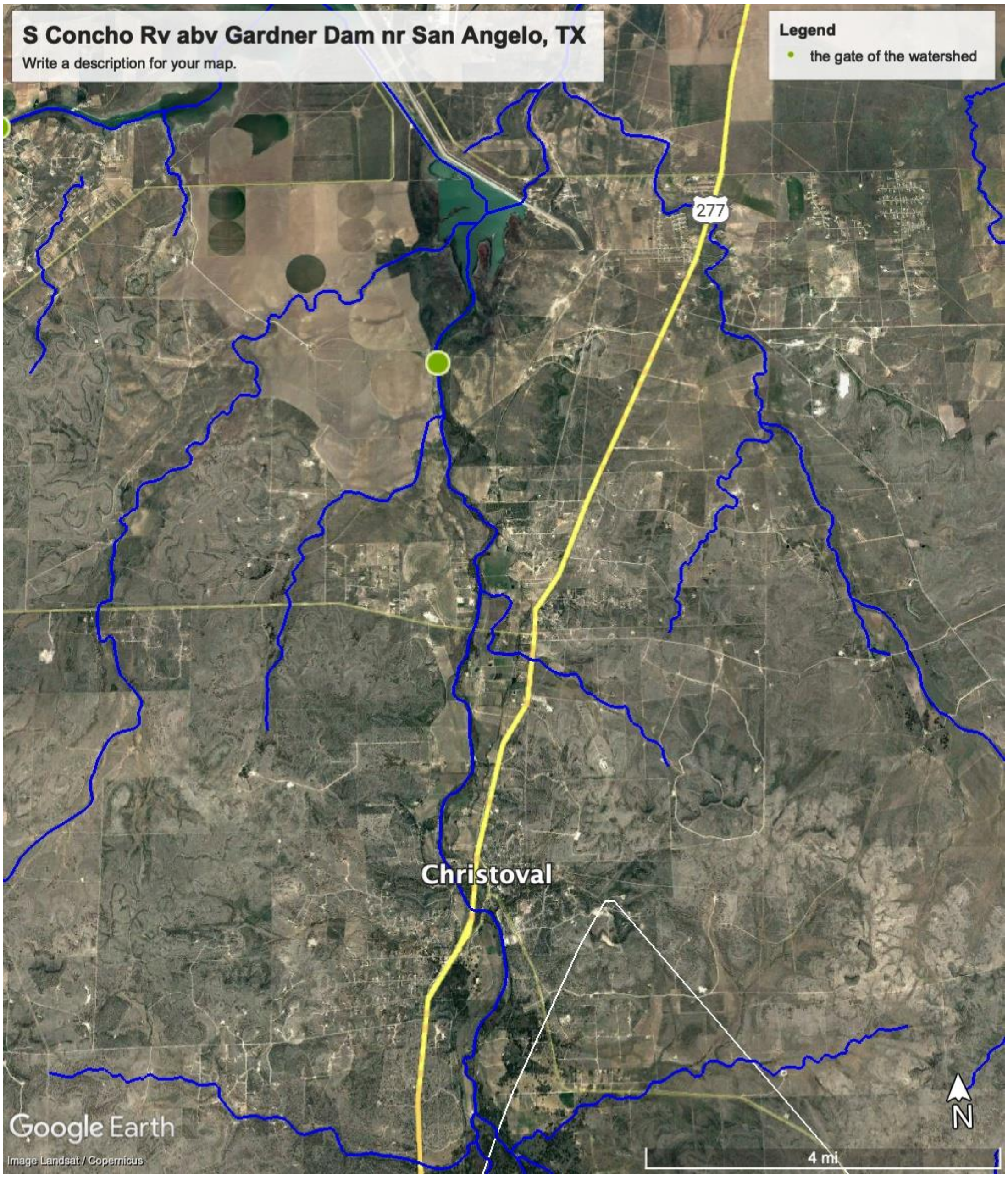


Figure 24. Map of the S Concho River above Gardner Dam near San Angelo as the gate of the watershed within Tom Green

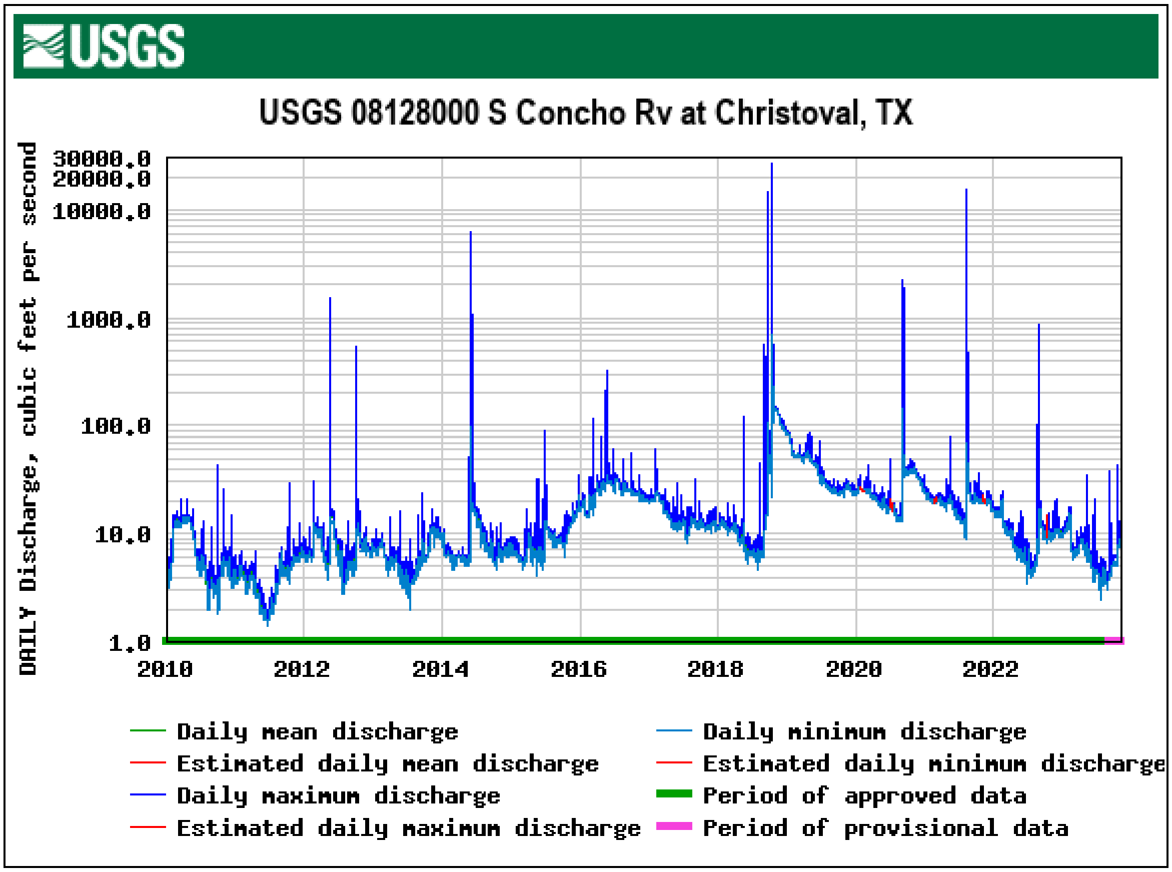


Figure 25. daily discharge of S Concho River at Christoval, TX between 2010 and 2020 .

Daily precipitation was also tested in a region outside the cloud seeding area namely, Concho River at Paint Rock, TX.

Figure 26. Map showing Concho River at Paint Rock, TX From google earth.

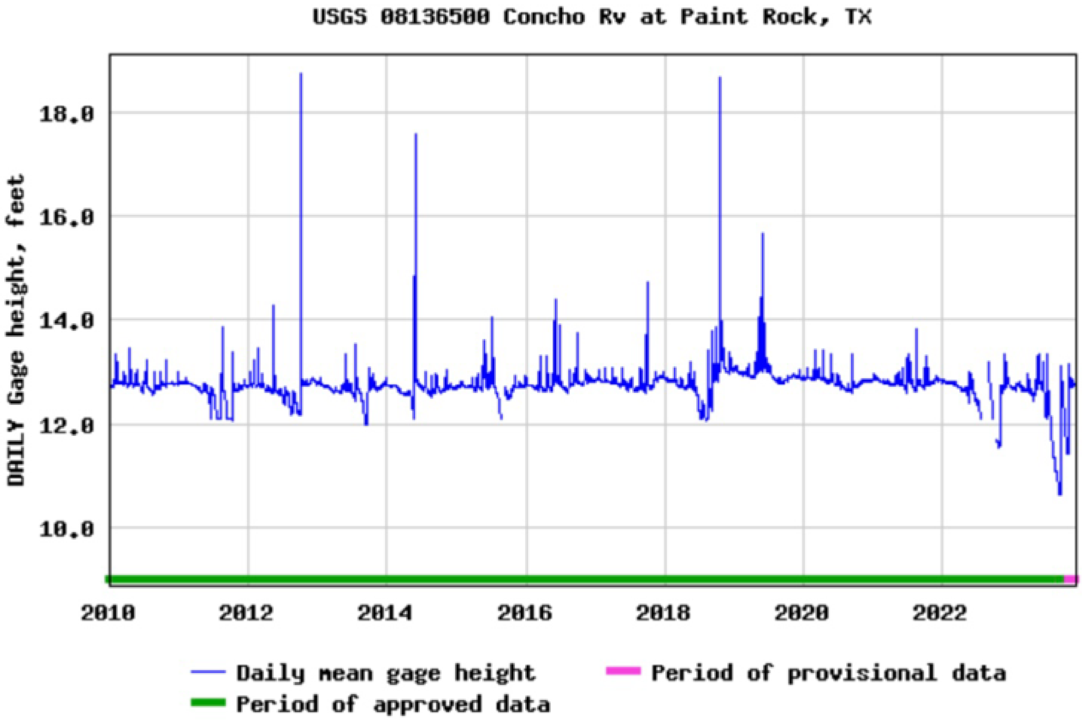


Figure 27. Daily discharge of Concho River at Paint Rock, TX between 2010 and 2020.

The average weighted CN of S Concho River at Christoval of S Concho River at Christoval is 61.99 and 62.08. A value of 62 is used to calculate the storm runoff using the estimated precipitation in non-seeding scenario and the runoff of seeding scenario.

The maximum potential storage of the watershed is 6.11, it was calculated using equation (2). The importance of calculation the potential storage is to calculate the runoff in precipitation event, equation (1), all amount was converted to inches to do calculations (Table 5).

Table 6. Total precipitation and total runoff in S Concho River at Christoval, TX area in seeding and non-seeding events, Y: Yes, N: No for cloud seeding.

Year	Total precipitation [mm]		Runoff [mm]	
	N	Y	N	Y
2015	148.844	230.124	50.8	111.501
2016	147.574	206.248	49.784	92.71
2017	164.338	216.408	61.214	100.584
2018	116.078	193.04	29.972	82.55
2019	283.718	358.902	156.21	222.25
2020	169.418	223.012	54.864	105.918

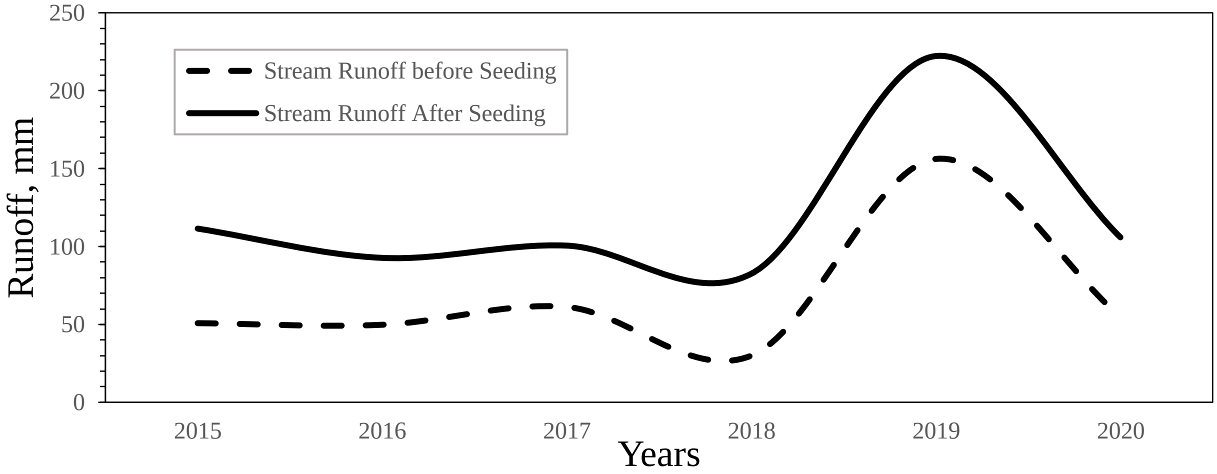


Figure 28. Estimated average stream runoff (the additional water that land absorbs) in S Concho River at Christoval, TX before and after the cloud seeding.

According to the results, the estimated average of stream runoff before seeding is 67.056 mm. the enhancement of rain precipitation resulted increase of the stream runoff average to 119.125 mm.

4. Discussion

Before cloud seeding, the water quality and ecosystem in the San Angelo area would primarily be influenced by natural factors and human activities unrelated to cloud seeding, such as agricultural runoff, urban development, and natural weather patterns. Watershed ecosystems would typically be adapted to the natural variability of precipitation and runoff, with species composition and water chemistry reflecting the prevailing natural conditions. After initiating cloud seeding operations with AgI, several outcomes might be hypothesized. The primary goal of cloud seeding is to increase precipitation. This could lead to higher runoff levels and potentially more water flowing through the watershed. The increased water availability could benefit the ecosystem, especially in drought-prone areas, by supporting a wider range of plant and animal life and improving the health of aquatic ecosystems. The impact of cloud seeding on water quality is a subject of debate among scientists. Silver iodide is considered to be relatively insoluble in water and has a low toxicity to aquatic and terrestrial life at the concentrations typically used in cloud seeding operations[47]. However, long-term or large-scale operations could potentially accumulate concentrations that might pose risks. Studies specifically examining these effects are necessary for conclusive assessments. Changes in precipitation patterns can alter ecosystems. Increased water availability could shift vegetation patterns, encourage the growth of certain species over others, and potentially alter habitats. While some changes could be positive, such as increased plant growth, there could also be negative impacts if the changes favor invasive species or alter the natural fire regimes[62]. Concerns about the accumulation of AgI and its potential impacts on soil and water ecosystems are often discussed. However, research suggests that the concentrations of AgI resulting from cloud seeding are generally below levels expected to cause environmental harm[47]. Nonetheless, continuous monitoring is essential to ensure that the cumulative effects do not pose a risk to the environment.

CHAPTER 5 : EVALUATING CLOUD SEEDING'S ROLE IN ATMOSPHERIC AEROSOLS AND AIR QUALITY DYNAMICS.

1. Introduction.

Cloud seeding, a weather modification technique aimed at enhancing precipitation by introducing substances such as silver iodide or other salt particles into clouds, has been a subject of ongoing research and debate worldwide. One significant aspect of this practice is its potential impact on aerosols and particulate matter in the atmosphere. The interaction between cloud seeding activities and aerosols can have varied effects on air quality, atmospheric composition, and environmental processes. However, the extent of these impacts are not uniform and can differ significantly based on a range of factors, including geographical location, meteorological conditions, existing air pollution levels, cloud dynamics, and the specific cloud seeding techniques employed[63]. Understanding these factors is crucial for assessing the environmental implications of cloud seeding and implementing effective strategies to manage air quality and precipitation enhancement in different regions. This research explored how the impact of cloud seeding on aerosols and particulate matter in the air varies from location to location, shedding light on the complex interactions between weather modification practices and atmospheric constituents.

2. Factors impacting on cloud seeding efficiency

2.1. Geographical Location factor.

Geographical location plays a crucial role in determining the impact of cloud seeding on air quality and particulate matter due to variations in meteorological conditions, atmospheric composition, and local environmental factors[64]. Different regions have unique atmospheric conditions, such as humidity levels, temperature, and wind patterns, which can affect how cloud seeding materials disperse and interact with existing aerosols. The effectiveness of cloud seeding in enhancing precipitation and its impact on air quality can vary based on these atmospheric factors. The topography of a region can influence cloud dynamics, precipitation patterns, and aerosol dispersion. Mountainous areas, for example, may experience different responses to cloud seeding compared to flat terrain due to variations in cloud formation and atmospheric circulation[65]. This can impact the distribution of atmospheric particulate matter. Geographical location can also influence the baseline levels of air pollution in a region. Cloud seeding activities may interact with existing pollutants in the atmosphere, potentially affecting air quality and particulate matter concentrations differently in areas with varying pollution levels. Different regions experience diverse meteorological conditions, such as frequency of cloud formation, precipitation rates, and atmospheric stability[64]. These factors can influence the success of cloud seeding operations and the subsequent impact on air quality and particulate matter dynamics[64].

2.2. Meteorological Conditions factor.

Meteorological conditions play a crucial role in determining the impact of cloud seeding on air quality and particulate matter in the atmosphere[66]. The success of cloud seeding operations and their effects on aerosol concentrations and air quality are influenced by various meteorological factors[66]. Meteorological conditions such as cloud type, cloud base height, and vertical motion can affect the formation and development of clouds suitable for seeding. The availability of moisture and updrafts in the atmosphere can impact the efficiency of cloud seeding and subsequent precipitation enhancement[66]. The stability of the atmosphere, characterized by factors like temperature inversions and vertical mixing, can influence the dispersion and behavior of seeding agents and aerosols. Meteorological conditions that promote atmospheric stability may impact the spread and longevity of cloud seeding effects on air quality. Wind speed and direction play a role in the transport of aerosols and pollutants in the atmosphere[66]. Meteorological conditions that affect wind patterns can influence the distribution of seeding agents and aerosols, potentially impacting air quality in downwind regions. Temperature and humidity levels in the atmosphere influence cloud properties, such as cloud droplet size and evaporation rates. These meteorological conditions can determine the effectiveness of cloud seeding in generating precipitation and shaping the interaction between seeding agents and aerosols.

2.3. Existing Air Pollution Levels factor.

Existing air pollution levels play a significant role in determining the impact of cloud seeding on air quality and particulate matter. The interaction between cloud seeding activities and air pollution can influence the composition of aerosols in the atmosphere and ultimately affect air quality. Air pollution sources release a variety of aerosols into the atmosphere. When cloud seeding is conducted in areas with high levels of air pollution, the seeding agents introduced into clouds can interact with existing aerosols, potentially altering the composition and behavior of particulate matter in the air[67]. High levels of air pollution, such as particulate matter from industrial activities or vehicle emissions, can impact the efficiency of cloud seeding-induced precipitation[53]. Polluted air masses may contain additional aerosols that can serve as cloud condensation nuclei, affecting cloud microphysics and precipitation processes[53]. Cloud seeding activities can lead to changes in atmospheric dynamics and precipitation patterns, which may have implications for air quality. The removal of aerosols and pollutants through precipitation can improve air quality in some cases, while the introduction of additional particles from cloud seeding may exacerbate existing pollution levels[68]. The influence of existing air pollution levels on the impact of cloud seeding can vary regionally based on the sources and types of pollutants present in the atmosphere. Pollution profiles in urban, industrial, or rural areas can interact differently with cloud seeding activities and affect air quality outcomes[69].

2.4. Type of Cloud Seeding Techniques factor.

The method of cloud seeding, whether through the use of silver iodide, salt particles, or other substances, can influence the formation and properties of aerosols in the atmosphere[67]. Different techniques may have varying impacts on aerosol concentrations and composition[67]. The choice of cloud seeding technique can significantly influence the impact of cloud seeding on air quality and particulate matter in the atmosphere. Different cloud seeding methods involve the introduction of various seeding agents into clouds to stimulate precipitation, which can affect aerosol concentrations and air quality in distinct ways[70]. The composition of the seeding agent used in cloud seeding can influence the type and concentration of aerosols introduced into the atmosphere. The method of cloud seeding, whether through ground-based generators, aircraft dispersal can impact the distribution and dispersion of seeding agents and resulting aerosols. This can affect how cloud seeding activities interact with atmospheric particles and influence air quality[29]. Different cloud seeding techniques may target specific cloud types or conditions to enhance precipitation. The choice of technique based on cloud properties can affect the efficiency of precipitation enhancement and the subsequent impact on air quality and particulate matter concentrations[71]. The environmental implications of cloud seeding techniques, such as the potential for unintended consequences on air quality, should be carefully evaluated. Factors like the persistence of seeding agents in the atmosphere and their interactions with existing aerosols play a role in determining the overall impact on air quality.

2.5. Local Topography factor.

Local topography plays a significant role in influencing the impact of cloud seeding on air quality and particulate matter in the atmosphere[72]. The geographical features and terrain of a region can affect cloud dynamics, precipitation patterns, and the dispersion of seeding agents and aerosols, ultimately shaping the environmental consequences of cloud seeding. Topography can influence the formation and evolution of clouds through orographic lifting, where air is forced to rise over mountains or hills. Cloud seeding in regions with complex topography can lead to orographic enhancement of precipitation, affecting the distribution of aerosols and particulate matter in the atmosphere. Local topography can impact wind patterns and the movement of air masses, which play a role in the transport and dispersion of seeding agents and aerosols. Variations in topography can lead to differences in atmospheric circulation, affecting the impact of cloud seeding effects on air quality. Elevation changes associated with local topography influence atmospheric stability, temperature gradients, and moisture availability[72]. These factors can affect the effectiveness of cloud seeding techniques and their impact on precipitation and air quality in different microclimates within a region. Topographic features can act as barriers to the dispersion of pollutants and aerosols, leading to localized air quality impacts. Cloud seeding activities in areas with specific topographical characteristics may interact differently with existing particulate matter levels and air pollution sources.

3. Effect of cloud seeding failure on aerosols in the atmosphere.

The exploration of cloud seeding as a method to enhance precipitation and combat water scarcity has led to an increased interest in understanding its environmental impacts, particularly concerning aerosols in the atmosphere. Cloud seeding involves the introduction of particles, such as silver iodide or salt, into clouds to encourage ice nucleation or droplet coalescence, aiming to trigger precipitation. However, when cloud seeding efforts fail or do not produce the intended outcomes, there are potential implications for atmospheric aerosols, cloud properties, and local weather patterns. This review synthesizes current knowledge on the effects of unsuccessful cloud seeding on atmospheric aerosols.

Aerosols Cloud seeding materials, when introduced into the atmosphere, become part of the ambient aerosol population. The primary concern with failed cloud seeding operations is the potential alteration of the aerosol size distribution and composition, which can affect cloud microphysics and, consequently, cloud formation and precipitation processes[64]. Furthermore, the persistence of seeding agents like silver iodide in the atmosphere could influence nucleation processes, potentially leading to unintended cloud formation or suppression[73]. The introduction of additional aerosols into the atmosphere through unsuccessful cloud seeding can have broader environmental and climatic implications. For instance, aerosols can directly affect the Earth's radiative balance either by directly scattering sunlight back to space, or indirectly altering cloud reflectivity and lifetime[74]. In scenarios where cloud seeding fails to induce precipitation, these unintended aerosol effects could exacerbate climate change impacts or modify local weather patterns in unpredictable ways. Despite the potential implications, research specifically addressing the effects of failed cloud seeding on atmospheric aerosols is limited. Most studies focus on the outcomes of successful operations or the broader impacts of aerosols on climate and weather, leaving a gap in understanding the specific consequences of cloud seeding failures. Additionally, the complexity of atmospheric processes and the variability in cloud seeding practices across different regions make it challenging to generalize findings.

The effect of cloud seeding failure on atmospheric aerosols remains an underexplored area within the broader field of weather modification research. While theoretical and modeling studies provide insights into possible impacts, there is a critical need for empirical research to assess the real-world consequences of seeding agent dispersion in the atmosphere. Future studies should aim to quantify the persistence and behavior of seeding materials under various atmospheric conditions and their implications for aerosol-cloud interactions, weather patterns, and climate.

4. Failure of cloud seeding events identification

4.1. Introduction

Identifying and analyzing cloud seeding failures is pivotal for advancing our understanding of weather modification techniques and their efficacy. Despite the potential of cloud seeding to enhance precipitation, there are notable instances where such interventions have not led to the desired outcomes. This review delves into the literature on cloud seeding failures, highlighting the importance of rigorous evaluation and the factors contributing to these unsuccessful attempts. A significant challenge in identifying cloud seeding failures lies in the inherent variability of weather and the difficulty in establishing clear cause-and-effect relationships. Weather patterns are influenced by a myriad of factors, making it challenging to isolate the impact of cloud seeding activities[25]. Furthermore, the definition of "failure" can vary, depending on whether the focus is on the lack of precipitation increase, unintended environmental impacts, or cost-effectiveness. Several factors can contribute to the failure of cloud seeding efforts, including unsuitable meteorological conditions, inadequate seeding material or techniques, and insufficient understanding of local cloud and aerosol properties. For instance, research has shown that the effectiveness of cloud seeding can vary significantly with the type of clouds targeted and the atmospheric conditions present during seeding operations[75]. The mixed results and instances of failure underscore the importance of rigorous, systematic evaluation of cloud seeding projects. This involves not only comprehensive planning and execution of seeding operations but also the utilization of control areas and advanced statistical methods to assess outcomes accurately[5].

4.2. Notable failure events

The Wyoming Weather Modification Pilot Project, conducted over a decade starting in 2005, aimed to assess the feasibility and effectiveness of winter orographic cloud seeding to enhance snowpack in the Medicine Bow, Sierra Madre, and Wind River mountain ranges. Despite the extensive duration and investment, the project concluded with mixed results. The final report indicated that while there were some positive signals, the statistical evidence was not strong enough to conclusively demonstrate the effectiveness of cloud seeding in increasing snowfall or water resources in the targeted areas[9]. The Queensland Cloud Seeding Research Program in Australia was initiated in response to severe drought conditions. The program, which ran from 2007 to 2008, aimed to investigate the potential for cloud seeding to increase rainfall in the region. However, the program faced challenges in attributing any observed increases in precipitation directly to cloud seeding efforts due to the natural variability of rainfall and the lack of a comprehensive control setup. The final assessment reported difficulties in distinguishing the effects of seeding from other meteorological factors, leading to inconclusive results[76]. A long-term cloud seeding experiment has been conducted in middle east from 1961 to 2000, using silver iodide to seed cumulus clouds with the goal of enhancing rainfall. A comprehensive evaluation of the experiment published in 2007 suggested that the initial positive results might have been overestimated. Statistical reanalysis showed no significant increase in rainfall that could be directly attributed to cloud seeding activities, calling into question the efficacy of the program[77].

While cloud seeding holds promise as a tool for weather modification, the examination of failed or inconclusive cloud seeding operations highlights the complexities and challenges associated with weather modification By analyzing unsuccessful attempts, researchers can gain insights into the complex interplay between seeding materials, atmospheric conditions, and precipitation processes. Continued research, coupled with transparent reporting and evaluation, will be essential for advancing the science of cloud seeding and realizing its potential benefits.

5. Conclusion

Given the detailed review on the impact of cloud seeding on air quality and particulate matter dynamics, we can match the findings with the specified factors. In UAE, local weather conditions during cloud seeding missions contributed to the degradation of silver iodine crystals, resulting in a higher chance of coarse particle formation. Additionally, high summer temperatures and relative humidity were mentioned as factors increasing anthropogenic aerosol loadings. The analysis considered the baseline air quality and particulate matter levels, suggesting that cloud seeding could have implications for air quality and human health due to the increase in PM concentrations, especially PM10 and PM2.5. The use of silver iodide crystals as a technique of cloud seeding missions was specifically mentioned. This technique led to a temporary increase in PM10 concentrations due to the degradation of these crystals into smaller particles. In China, While the specific meteorological conditions during cloud seeding operations in China were not detailed in the provided text, the general implication is that weather conditions can influence the effectiveness and environmental impact of cloud seeding. The studies highlighted concerns about the introduction of additional particles into the air through the seeding process, indicating an awareness of the existing air pollution levels as a critical factor. Although the specific types of cloud seeding techniques used in China were not detailed, the mention of changes in aerosol properties and concentrations suggests a focus on the techniques' impact on air quality. In San Angelo, TX, The temporary nature of changes in AOD and AE levels following cloud seeding suggests that meteorological conditions play a role in the transient impact of cloud seeding on atmospheric aerosol properties. The study's focus on immediate changes in aerosol optical properties following cloud seeding operations implies a consideration of the baseline air quality and particulate matter levels. The introduction of seeding agents such as silver iodide (AgI) and the observed aggregation of smaller aerosol particles around these agents point to the specific techniques used and their immediate environmental impacts. In summary, Existing Air Pollution Levels are a crucial backdrop against which the effects of cloud seeding on air quality are measured, highlighted in discussions about the UAE and China. Type of Cloud Seeding Techniques factor directly impacts the observed changes in particulate matter dynamics and air quality, particularly noted in the UAE and San Angelo, TX cases. The Local topography factor was not explicitly connected to any of the findings in the provided text, suggesting that the studies focused more on atmospheric chemistry and meteorology than on geographical features influencing cloud seeding outcomes.

In conclusion, the review of cloud seeding's impact on air quality and particulate matter dynamics across different geographical regions, including the United Arab Emirates, China, and San Angelo, Texas, presents a nuanced understanding of the interactions between cloud seeding operations and atmospheric conditions. The findings underscore the importance of considering a variety of factors when assessing the environmental implications of cloud seeding activities. These factors include meteorological conditions, existing levels of air pollution, and the specific techniques of cloud seeding employed. The evidence suggests that cloud seeding can influence particulate matter concentrations in the atmosphere, with the potential for both increasing and decreasing PM10 and PM2.5 levels. This variation is largely dependent on the local weather conditions at the time of seeding, the baseline air quality, and the specific methods and materials used in cloud seeding operations. While some studies highlighted temporary increases in aerosol loading following cloud seeding, attributed to the introduction of seeding agents like silver iodide, others pointed to the potential for cloud seeding to reduce fine dust concentrations through enhanced precipitation and aerosol washout. However, the environmental impacts of cloud seeding are complex and multifaceted. The transient nature of the changes observed in aerosol optical properties suggests that cloud seeding does not result in long-term alterations to atmospheric composition. Nonetheless, the immediate effects, such as the temporary increase in particulate matter concentrations, warrant careful consideration, especially in regions with existing air quality issues. Further research is essential to fully understand the long-term impacts of cloud seeding on air quality, precipitation patterns, and climate. Such studies should take into account the varying meteorological conditions under which cloud seeding is performed and explore the implications of different seeding agents and techniques. Ultimately, the goal should be to balance the benefits of increased precipitation through cloud seeding with the need to protect and improve air quality, ensuring environmental sustainability and public health. This review highlights the critical need for a comprehensive approach to cloud seeding, one that carefully weighs its potential benefits against the possible environmental costs. As we move forward, the integration of advanced monitoring technologies and more sophisticated modeling techniques will be crucial in developing cloud seeding strategies that are both effective and environmentally responsible.

The investigation into the impact of cloud seeding on aerosol optical depth (AOD), particulate matter, and the various factors that could influence these effects has underscored the complexity and variability inherent in atmospheric science. Through detailed analysis, this study has illuminated how cloud seeding operations can transiently alter atmospheric conditions, affecting AOD and particulate matter concentrations. Moreover, the discussion on the multitude of factors-ranging from the specific characteristics of the seeding agent to local meteorological conditions-reveals the intricate interplay that determines the outcome of such interventions. It becomes evident that research findings on the success of experiments in the field of cloud seeding and its atmospheric impacts are markedly influenced by the unique conditions present at each location. The specifics of the seeding operations conducted, and the prevailing meteorological scenarios at the time of seeding. This variability not only challenges the generalization of results but also highlights the necessity of contextual evaluation. Consequently, the assertion that each cloud seeding project must be assessed independently, considering the specific circumstances and environmental settings, is strongly validated by the findings of this research. The importance of conducting numerous long-term evaluations cannot be overstated. Given the transient nature of the impacts observed, long-term studies are crucial for understanding the cumulative effects of cloud seeding on atmospheric aerosols and particulate matter. Such comprehensive assessments will enable a more nuanced understanding of cloud seeding as a viable weather modification technique, ensuring that its application is both scientifically grounded and environmentally responsible. In conclusion, this thesis emphasizes the need for a location-specific and long-term approaches to evaluating the impacts of cloud seeding. By acknowledging the diverse factors that influence the effectiveness and environmental consequences of cloud seeding, this research contributes to refined and responsible applications of weather modification technologies.

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