

# The *modus operandi* of Cloud Seeding for Rain Enhancement: An Overview for Non-Scientific Audiences

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**Abstract:** Cloud seeding is a weather modification technique that requires mastery of a myriad of disciplines, including cloud physics, cloud studies, meteorology, atmospheric physics, and chemistry. The process of cloud seeding, as described in current literature, is complex in both its practice and terminology. It is often difficult for lay audiences, such as the public, policymakers, the media, and local stakeholders, to understand cloud seeding methods, and there is no single comprehensive work that explains them. Additionally, the governance of cloud seeding involves legal, economic, and political considerations that cross disciplines. It is important to explain its techniques in simple language to raise public awareness and support policymaking, and to involve legal, economic, and political experts outside the sciences. Therefore, the knowledge deficit model, using a qualitative approach, is used in this article to explain how cloud seeding works to larger non-scientific audiences.

**Keywords:** Cloud-Seeding; *modus operandi*; Cloud Condensation Nuclei; Seeding Agents; Cloud Types.

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## I. INTRODUCTION

Cloud Seeding is a weather modification technique that deliberately intervenes in the Earth's atmosphere to influence local weather conditions, e.g., by enhancing rain. Generally, weather modifications are twofold: benign and hostile. Benign weather modification entails peaceful purposes, i.e., cloud seeding to address drought. In contrast, hostile purposes known as weather warfare or environmental warfare, where the environment is manipulated for military purposes (Westing, 1984, p.1), i.e., during the Vietnam War, Operation Popeye (1967-1972) executed cloud-seeding to extend the monsoon season, particularly on Ho Chi Minh Trail to disrupt enemy supply routes through increased rainfall and muddy conditions.

In a broad sense, cloud seeding can be used in both ways to augment rainfall or increase mountain snowpack (DRI, 2023); however, the scope of this article is confined to rain-inducing technology. Generally, to augment precipitation, cloud-seeding introduces chemical agents, i.e., silver iodide (AgI), dry ice (Solid CO<sub>2</sub>), sodium chloride/ common salt (NaCl), calcium chloride (CaCl<sub>2</sub>), liquid propane (C<sub>3</sub>H<sub>8</sub>), potassium chloride (KCl), urea, etc., to clouds via various aerial, ground-based, and drone-based seeding mechanisms. The discovery of cloud-seeding was first demonstrated by I. Langmuir (IMD, 2018) and Vincent J. Schaefer at the General Electric Research Laboratory, New York by carrying out the

first successful field test using dry ice on 13 November 1946 (General Electric Research Laboratory, 1952) and followed by Bernard Vonnegut discovering AgI as an effective ice-nucleating agent in 1947 (Vonnegut, 1947). These innovations have inspired the cloud-seeding experiments to date.

Applications of cloud-seeding includes; increasing rainfall during droughts, dispersing fog especially at airports, water augmentation or reservoir replenishment, ground water enhancement, aquifer replenish, to mitigate air pollution (Dixit, 2024), reduce pollution by scavenging, power hydro-power plants and increase snowfalls for ski resorts (SSC, 2023, p.92) and even to reduce hail damage, forest fires and to control the rainfall in specific events, i.e. Beijing Olympics 2008 (Guinness World Records, 2008) and at British Royal wedding of Duke and Duchess of Cambridge in 2012 (Ghosh, 2019). While these benefits are applauding, its' alleged negative impacts yet remains doubtful seeking validity i.e. soluble silver iodide has potential to cause environmental and ecological impacts and even human health risks (Cooper and Jolly, 1970), alterations in natural weather patterns resulting unintended weather consequences (Felice et al, 2014) and alarming the water quality with reference to the values of total silver in drinking water (ASTDR, 1990). Hence, as an 80-year-old technology (GAO, 2024), cloud seeding is currently practiced in 39 (see Note 1) to 56 (see Note 2) countries, amid both benefits and criticisms.

It must also be noted that cloud-seeding is not a geoengineering method refers to the deliberate large-scale intervention in the earth's natural systems to manipulate earth's climate systems aimed at addressing global warming, i.e. removing greenhouse gases from the atmosphere (carbon dioxide removal –CDR) or by reflecting solar radiation into space (Solar radiation management – SRM) (Keith, 2000; Royal Society, 2009; National Research Council, 2015) and ocean fertilization (DOSI, 2021, p.1) Cloud-seeding is a localized weather modification technique that aims to induce precipitation by introducing substances into clouds to encourage droplet formation and rainfall. (Bruitjes, 1999). Further, geoengineering interventions are long-term, whereas cloud seeding has only short-term effects.

The literature review indicates that cloud-seeding science suffers from pressure to produce simplistic metrics. Due to a lack of basic scientific understanding of cloud seeding, the public, policymakers, the media, and local stakeholders are susceptible to rumors; for example, following widespread flooding in Dubai in April 2024, the public blamed the country's ongoing cloud seeding efforts. Another piece of misinformation is that seeding always produces rain, despite the scientific truth that seeding only helps with certain cloud types and atmospheric conditions. Additionally, an evidence gap exists on how to translate technical exposure assessments into locally meaningful messages, i.e., the aftermath of Project Cirrus in 1947, which unfolded a seeded hurricane with dry ice, changed the course of the storm, and it hit the coast of Georgia, leading to lawsuits against the General Electric Corporation. Further, variability in how effectiveness is measured makes technology seem unreliable or contentious to the public; i.e., some studies report increased rainfall, while others show no effect. Without clear communication about who benefits and who loses, cloud seeding also faces political resistance. Therefore, against the backdrop of sparse research on socio-economic framing as understandable to lay audiences, this article attempts to address these gaps in the literature.

The research methodology used is qualitative, relying on both primary and secondary sources. Primary sources include interviews with experts, while secondary sources consist of journal articles and books. The theoretical foundation of this study is the Knowledge Deficit Model, which posits that public disbelief in science stems from a lack of knowledge. The aim is to address this 'deficit' by providing simplified scientific information from experts to a passive public. The analytical framework combines the Empirical Explanative Method with an Interdisciplinary approach. The empirical explanatory model offers an overview of the current scientific understanding of cloud-seeding activities. The main goal of this paper is to explain the cloud seeding process, drawing on knowledge from cloud physics, cloud studies, meteorology, atmospheric physics, and chemistry, using straightforward language to enhance understanding among non-scientific audiences. To address the identified gaps in the literature and find practical solutions, an interdisciplinary approach is employed. This article focuses solely on cloud seeding to induce rain and does not cover cloud microphysics, which involves processes like cloud electrification.

The remainder of this article is as follows. Section 2 provides a prelude to exploring the Earth by discussing atmospheric layers and the hydrologic cycle. Section 3 steps into the direct subject matter of understanding clouds and cloud physics by evaluating cloud formation, cloud classification, cloud development, cloud seeding, and rain precipitation. Section 4 investigates cloud-seeding techniques by discussing seeding types; cloud-seeding agents; modes of cloud-seeding, i.e., aerial aircraft seeding, ground-based seeding, rocket seeding, artillery shell seeding, and drone-based seeding; and, lastly, the meteorological equipment involved in cloud-seeding. The main conclusions are presented in Section 5.

## II. EXPLORING THE EARTH

Bill Anders, the Apollo 8 astronaut who captured the famous 'Earthrise' photo during their first lunar orbit in December 1968, remarked, "We came all this way to explore the Moon, and the most important discovery was the Earth." (Lutgens and Tarbuck, 2014, p.24) The most striking element in this image is not the continents but the clouds floating over the seas and oceans, highlighting the vital role of water on Earth.

The four spheres of the Earth are: the geosphere (solid Earth), the atmosphere (gaseous envelope), the hydrosphere (water component), and the biosphere (life). Cloud seeding is a process that involves interactions between the atmosphere and hydrosphere, ultimately benefiting the geosphere and biosphere. Ahrens (2009, p.4) clearly explains the interdependence of the atmosphere and hydrosphere by stating that 'the earth without an atmosphere would have neither lakes nor oceans. There would be no sounds, no clouds, no red sunsets. It would be unimaginably cold at night and unbearably hot during the day. Moreover, the continual energy exchanges between the atmosphere and Earth's surface, as well as between the atmosphere and space, produce the effects known as 'weather'. (Lutgens and Tarbuck, 2014, p.25)

Thereby, it is apparent that the lack of a sound knowledge of atmosphere and hydrosphere of the Earth, disqualify the non-scientific audiences in understanding the *modus operandi* of cloud-seeding, as the atmosphere and hydrosphere is imperative to understand the basis behind the science and techniques of cloud seeding, as they stabilize weather and the water cycle of the earth by enabling cloud formation, precipitation and wind circulation. Therefore, the following bestows the basics of atmosphere and hydrosphere.

### A. Atmospheric Layers

On 14 October 2012, Felix Baumgartner became the first human to dive from the Stratosphere to Earth successfully. He ascended to an altitude of approximately 39 kilometers (approx. 128,000 feet) in a helium balloon, then jumped from the edge of space and landed safely in New Mexico, USA. (Howorth, 2012; Red Bull Stratos, 2012; Mott, 2012) The second to perform a successful space dive from the stratosphere to earth was Alan Eustace, on 24 October, 2014, by ascending to approximately 41.42 kilometers (135, 898

feet) using a helium balloon, breaking Baumgartner's 2012 altitude record as well as becoming the longest free-fall distance without drogue stabilization. (Refer Note 3) (BBC News, 2014; Markoff, 2014) Despite the excitement, this news would sound typical and hold no significance for lay audiences lacking basic knowledge of Earth's atmospheric layers.

The Earth's atmosphere is the gaseous mass blanketing the Earth, acting as a protective shield held in place by Earth's gravity. It is suspended in solid and liquid particulate matter. The composition of the atmosphere has evolved over the history of life on Earth and is now changing due to human activities. "The earth's first atmosphere, some 4.6 billion years ago, was most likely hydrogen and helium and hydrogen compounds, i.e., methane (CH<sub>4</sub>) and ammonia (NH<sub>3</sub>)" (Ahrens, 2009, p.10). The air is mostly invisible, tasteless, and odorless. "The ancient Greeks considered air to be one of the four 'elements' (other elements were earth, fire, and water). Leonardo da Vinci and later John Mayow suggested that air is a mixture consisting of one component that supports combustion and life ('fire-air') and the other that does not ('foul-air'). 'Fire-air' was isolated by Scheele in 1773 and independently by Priestley in 1774. It was named oxygen. 'Foul air' is now called nitrogen". (Wallace & Hobbs, 2006, p.153).

The atmosphere is composed mainly of nitrogen (N<sub>2</sub>) about 78%, oxygen (O<sub>2</sub>) about 21%, Argon (Ar) about 0.93%, carbon dioxide (CO<sub>2</sub>) about 0.04% and trace gases, i.e. neon (Ne), helium (He), methane (CH<sub>4</sub>), Krypton (Kr), hydrogen (H<sub>2</sub>) and water vapour (H<sub>2</sub>O). (Lutgens & Tarbuck, 2014, p.30) The composition of the air is not constant, as it varies from time to time and from place to place. (Lutgens and Tarbuck, 2014, p.29) The atmosphere in high mountains is thinner than at sea level as it is compressed by the pressure of the overlying atmosphere (Schlesinger and Bernhardt, 2020). As a result, it is possible to travel for many thousands of kilometers in any horizontal direction, but moving a mere eight kilometers above the surface would suffocate humans. (Ahrens, 2009, p.4) In fact, the Earth's atmosphere is unique as no other planet in our solar system has an atmosphere with the exact mixture of gases or the heat and moisture conditions necessary to sustain life.

Oxygen protects living organisms from scorching solar radiation, regulates temperature through the greenhouse effect, influences audibility, and enables weather and climate processes that sustain ecosystems and human activities. Although humans can survive without water for a few days, they cannot survive more than a few minutes without an atmosphere. Among these functions, Earth's atmosphere is central to this article's discourse, as it stabilizes Earth's weather and water cycle by enabling cloud formation, precipitation, and wind circulation.

As per meteorology, the Earth's atmosphere is divided into vertical layers. In fact, the literature reports various layer spans and classifications in scholarly work, and these differences are understood to stem from the diverse yardsticks considered, i.e., temperature and atmospheric mass. Earth's

atmosphere is divided into five vertical layers based on temperature variations. 1) Troposphere, up to about 12 km 2) Stratosphere from about 12-50km. 3) Mesosphere from 50-85km. 4) Thermosphere, about 85-600km, and 5) Exosphere, the outermost layer extending from 600km to about 10,000km, gradually fading into outer space.

Another division, as stated by Westing (1984, p.4), "the earth's atmosphere extends some hundreds of kilometers upwards, but becomes extraordinarily thin beyond 150km. Based on atmospheric mass, it is divided into the lower atmosphere, which accounts for more than 99% of the total mass, and the upper atmosphere, which accounts for less than 1%. Ahrens (2009, p.4) also agrees that almost 99% of the atmosphere lies within a mere 30km (19 miles) of the Earth's surface. The lower atmosphere extends upward to 55km. "It consists of the troposphere (0-12km up; about 87 percent of the total atmospheric mass) and the stratosphere (about 12-55km). The stratosphere is divided into the lower stratosphere (about 12-30km) and the upper stratosphere (about 30-55km). The upper atmosphere (above about 55km) consists of the mesosphere (about 55-80km) and the thermosphere, also called the 'ionosphere' (about 80 – a few hundred km).

The atmosphere is further divided into layers based on its composition, namely the homosphere and the heterosphere. Below the thermosphere, the composition of air remains fairly uniform (78% nitrogen, 21% oxygen) due to turbulent mixing, and this layer is known as the homosphere. The region from about the base of the thermosphere to the top of the atmosphere is often called the heterosphere. (Ahrens, 2012, p.17) The atmosphere of the Earth ends at 100km above the Earth, also known as the "Von Karman" line (Diederiks-Verschoor & Kopal, 2008, p.17; Cheng, 1997, p.4), which marks the extent of the homosphere.

In this context, for cloud seeding, the important atmospheric layer where clouds develop vertically is the troposphere (the lower atmosphere, 0-12km). The article limits its elaboration of atmospheric layers to the troposphere. The troposphere is the first layer of the atmosphere. Troposphere (up to about 12 km), term derived from Greek tropein (Ahrens, 2009, p.12) meaning to 'turn or change' (Ahrens, 2009, p.12; Wallace & Hobbs, 2006, p.11), generally decreasing temperatures with height. In the bottom layer we live in, the troposphere, up to 8 km, temperature decreases with altitude at the environmental lapse rate, averaging 6.5°C per kilometer (3.5°F per 1000 feet), a figure known as the normal lapse rate. (Lutgens & Tarbuck, 2013, p.39; Wallace & Hobbs, 2006, p.11) It contains about 80% of the atmospheric mass and weather phenomena. (Schlesinger and Bernhardt, 2020) Lutgens & Tarbuck (2013, p. 39) further note that, in studying the results of more than 200 balloon launches, Teisserenc de Bort found that the temperature stopped decreasing and leveled off at an altitude between 8 and 12 kilometers (5 and 7.5 miles). Accordingly, the term 'troposphere' was coined in 1908 by Teisserenc de Bort and literally means the region where air "turns over," a reference to the appreciable vertical mixing of air in this lowermost zone (The Atmosphere, 2021, p.135). As explained by Westing (1984, p. 4), the troposphere is turbulent, windy, and

contains clouds. First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size. If you are using US letter-sized paper, please close this file and download the file “MSW\_USltr\_format”.

### B. Hydrologic Cycle

The Earth is called the ‘blue planet’, because water makes it irreplaceable. The hydrosphere is an active mass that is continually on the move, evaporating from the oceans to the atmosphere, precipitating to the land, and running back to the ocean again, which is called the hydrologic cycle. This further underscores the high likelihood that the water we drink is the same water dinosaurs were gulping about 65 million years ago. (Washington State University, 2022)

The word ‘hydra’ is derived from the Greek ‘water-snake’. Later, the term acquired the Proto-Indo-European root ‘wed’, meaning ‘water’ or ‘wet’. A water molecule consists of two hydrogen atoms and one oxygen atom and exists in three states: gas (water vapor), liquid (liquid water), and solid (ice). The gaseous composition of water was elaborated in the preceding session under the atmospheric layers. Liquid water resembles the global ocean. It covers 72% of the area of the Earth’s surface, and the mass of the ocean is 250 times as large as that of the atmosphere (Wallace & Hobbs, 2006, p.25). Further, the hydrosphere includes fresh water found in clouds, streams, lakes, glaciers, and underground. (Lutgens and Tarbuck, 2014, p.25-26). Solid water, or cryosphere, i.e., Antarctica and Greenland, contributes to the thermal inertia of the climate system, to the reflectivity (albedo) of the Earth, and, as a fresh water source in the Polar Regions, influences oceanic thermohaline circulation and stores enough water to influence global sea level significantly. (Wallace & Hobbs, 2006, p.32).

Hydrologic cycle composed of vast currents of water vapour, ice and associated energy which has operated for billions of years, flowing water throughout earth’s lower atmosphere, hydrosphere (the liquid part of the earth, i.e. the oceans), biosphere (the living component of the environment i.e., all of the biota; flora and fauna) and lithosphere (solid part of the earth i.e. land) to several kilometres beneath the surface. Once precipitation falls into an ocean, the water is ready to begin its cycle again. When it falls on a continent, it returns to the ocean in a complex journey. This cycle of moving and transforming water molecules from liquid to vapor and back to liquid is called the hydrologic cycle. (Ahrens, 2009, p.90) The residence time of a water molecule in any component of the cycle, and its effect on climate, are variable. As per Christopherson & Birkeland (2015, p.254), “water has a short residence time in the atmosphere, an average of 10 days, when it plays a role in temporary fluctuations in regional water patterns. Water has a longer residence time in deep-ocean circulation, groundwater, and glacial ice (as long as 3000-10,000 years), where it helps moderate temperature and climate change. They further emphasize that the parts where water is stored and released over long periods can have a “buffering effect” during periods of water shortage.

For understanding precipitation, the water in the atmosphere is evaluated through evaporation, transpiration, and evapotranspiration. Evaporation and transpiration together make up evapotranspiration, which represents 14% of the water entering Earth’s atmosphere. (Christopherson & Birkeland, 2015, p.255) It is observed that precipitation that reaches Earth’s surface as rain follows two basic pathways: it either flows overland or soaks into the soil. Meanwhile, interception also occurs when rain lands on vegetation or other ground cover. After reaching the ground surface via rain or snowmelt, water infiltrates the subsurface as it penetrates the soil. If the ground surface is impermeable (does not permit the passage of liquids), the water will begin to flow downslope as ‘overland flow’ or ‘surface run-off’. Water in the subsurface indicates that water that infiltrates into the subsurface moves downward into soil or rock by ‘percolation’.

Particularly for cloud seeding, it is more relevant to understand atmospheric water. ‘The air in the Sahara in the scorching heat and drought of summer may contain more vapor than the obviously damp air of a dull winter day in England’ (Kendrew, 1949, p.177; Ahrens, 2009, p.90). Within the atmosphere, there is an unending water cycle that involves three natural processes: evaporation, condensation, and saturation.

Evaporation: Sun’s energy causes the water molecules at the surface of the water to evaporate (changing from liquid into vapor). “Since an increase of heat from the sun results in an increase of evaporation, consequently of rainfall, the surface temperature of earth’s atmosphere can be cooler in years” (Grant, 1944, p.267). Humidity means the amount of water vapor (H<sub>2</sub>O) in the air. A moist day suggests high humidity.

Condensation: (changing vapor into liquid). While moist air is transported across regions by wind, water vapor condenses back into liquid water. Water vapor also releases large amounts of heat, called ‘latent heat’, which changes vapor into liquid water or ice. The water vapor molecules are invisible. They become visible only when they transform into larger liquid or solid particles, i.e., cloud droplets and ice crystals. (Ahrens, 2009, p.6) Accordingly, condensation results in dew, fog, and clouds. i) Dew: at the dew point (refer to Note 5), surfaces get cooled below this temperature, and water vapor begins to condense upon them, forming tiny visible specks of water called dew. When the dew point temperature is at or below freezing, frost forms. (Ahrens, 2009, p.112) ii) Fog: as the relative humidity of the air increases, the visibility decreases, and the landscape becomes masked with a greyish tint. When visibility drops below 1 km, and the air is filled with countless millions of tiny floating water droplets, the wet haze becomes a cloud resting near the ground, called fog. (Ahrens, 2009, p.114) iii) Cloud: it is an aggregation of tiny moisture droplets and ice crystals that are suspended in air and are great enough in volume and concentration to be visible, which may grow in size and fall to the surface as precipitation via rain, snow, or hail.

Saturation: The air cools to the dew point, which is the temperature at which saturation occurs. (Ahrens, 2009, p.112) For every molecule that evaporates, one must condense, so there is no net loss of liquid or vapor molecules. (Ahrens, 2009, p.92) The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

### III. UNDERSTANDING CLOUDS & CLOUD PHYSICS

The sun and the planets are believed to have formed 4.5 billion years ago from the gravitational collapse of a cold cloud of interstellar gas and dust. (Wallace & Hobbs, 2006, p.48) “As millions of years passed, the constant outpouring of gases from the hot interior, known as ‘outgassing’, provided a rich supply of water vapor, which formed into clouds. Rain fell upon the earth for many thousands of years, forming the rivers, lakes, and oceans of the world.” (Ahrens, 2012, p.10) Although clouds are beautiful paintings in the sky, they are essential gauges of overall weather conditions, including stability and moisture content. In 1788, Erasmus Darwin was the first person to suggest that clouds form by the adiabatic cooling of moist air (King-Hele, 1998) Although John Dalton had suggested in 1793 that clouds may consist of water drops that are continually descending relative to the air, it was not until 1850 that James Espy clearly recognized the role of upward-moving air currents in suspending cloud particles. (Wallace & Hobbs, 2006, p.209)

#### A. Cloud Formation

The first conference on the physics of cloud and precipitation particles was held at the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts, from September 7-10, 1955. During the conference, cloud-physics scientists gathered to formulate cloud physics as a science, where rainmaking is fast becoming a science of its own, and while gaining respectability in the eyes of fellow scientists in allied fields, Milton Greenberg commented, “the greatest danger which this new science faces, in my opinion, is the possibility that in its enthusiasm it will try to outrun itself before it is ready... we cannot afford to run before we have learned to walk” (Weickmann, 1955, p. xv)

Cloud is formed when the air at some height above the surface is cooled sufficiently below its dew point to condense its vapor. If condensation continues, the particles coalesce into drops or crystals of ice, large enough to fall as precipitation. (Kendrew, 1949, p.186). “A moisture droplet is approximately 20 micrometers in diameter (0.002cm or 0.0008 inches). It takes a million or more such droplets to form an average raindrop with a diameter of 2000 micrometers (approximately 2cm or 0.078 in.)” (Christopherson & Birkeland, 2015, p.208; Houghton, 1958, p.10)

The concentrations of nuclei influence the microstructures of clouds. The growth of precipitation particles is a result of instabilities that exist in the microstructures of clouds. The condensation process that produces clouds is not quite so simple. “Although the air may look clean, it never really is. On an ordinary day, a volume of air about the size of the index finger contains between 1000 and 150,000 particles. Since many of these serve as surfaces on which water vapor can condense, they are called ‘condensation nuclei’. Some condensation nuclei are quite small and have a radius less than 0.2  $\mu\text{m}$ ; these are referred to as ‘Aitken nuclei’, after the British physicist who discovered that water vapor condenses on nuclei. Particles ranging in size from 0.2 to 1  $\mu\text{m}$  are called ‘large nuclei’, while others, called ‘giant nuclei’, are much larger and have radii exceeding 1  $\mu\text{m}$ .” (Ahrens, 2009, p.113) These nuclei, may originate from many sources, typically come from dust, soot and ash from fires of volcanoes, factory smoke, forest fires and salt from ocean spray, particles from burned fuel i.e. sulphate aerosols, pollen and microorganisms lifted by the wind (Christopherson & Birkeland, 2015, p.208; Lutgens and Tarbuck, 2013, p.32; Ahrens, 2009, p.113) and even sulphate particles emitted by phytoplankton (microscopic marine algae) in the oceans (Ahrens, 2009, p.113). These tiny solid and liquid particles are called aerosols. (Lutgens and Tarbuck, 2013, p.32)

The condensation nuclei, which are most favorable for producing clouds (Cloud Condensation Nuclei or CCN), have radii of 0.1  $\mu\text{m}$  or more. Usually, between 100 and 1000 nuclei of this size exist in a cubic centimeter of air. (Ahrens, 2009, p.113) The number concentration and size spectrum of cloud droplets can also vary dramatically, depending on the CCN size distribution. A maritime droplet spectrum will consist of fewer particles but more large drops than in a continental spectrum. (Bruitjes, 1999, p.808) Condensation nuclei are extremely light (many have a mass less than one-trillionth of a gram), so they can remain suspended in the air for many days. They are most abundant over industrial cities, where highly polluted air may contain nearly 1 million particles per cubic centimeter. (Ahrens, 2009, p.113) In fact, in maritime air masses, nuclei average 1 billion per cubic meter and include sea salts derived from ocean sprays. (Christopherson & Birkeland, 2015, p.208)

The concentrations of CCN active at various supersaturations can be measured with a thermal diffusion chamber. (Wallace & Hobbs, 2006, p.214) Given the presence of saturated air and atmospheric cooling (lifting) mechanisms, cloud condensation will occur. Clouds were produced in the US Weather Bureau’s giant cloud chamber in Washington, D.C., to bring cloud processing under scientific control within the laboratory. (Houghton, 1958, pp.6-7) Since it is most difficult to accurately duplicate natural conditions in the laboratory, more extensive investigations of natural supercooled clouds became increasingly important, as Findeisen (1940) and Lueder (1951) attempted. The Mount Washington Observatory in New Hampshire, therefore, launched an experimental project in 1954 to address questions along these lines. (Houghton, 1958, p. 33) There are also records of clouds produced by the US Weather Bureau in Washington, DC. (Houghton, 1958, pp. 6-7) Further, reports

by Professor Pierre Gendron on work done under Air Force contracts indicate that he employed a modified Langsdorf diffusion cloud chamber and found that various nuclei became active at different supersaturation ratios. He has tested six salts in his diffusion cloud chamber: lithium chloride (LiCl), sodium chloride (NaCl), calcium chloride (CaCl<sub>2</sub>), manganese chloride (MnCl<sub>2</sub>), copper sulfate (CuSO<sub>4</sub>), and silver iodide (AgI). (Birstein, 1955, p.145-147)

To form a cloud, in addition to sufficient water, other significant factors include the range of droplet sizes, cloud thickness, the cloud's updrafts, the electric charge of the droplets, and the electric field within the cloud. (Ahrens, 2009, p.169) The Clouds may contain raindrops, but not initially. The fundamental difference between the electrification of the cloud droplet and the rain drop is that “the cloud droplet encounters ions by their thermal agitation, whereas the raindrop is bombarded as a result of the relative gravitational motions” (Houghton, 1958, p.20). An ordinary cloud droplet is extremely small, with an average diameter of 20 μm (0.002 cm). “A typical cloud droplet is 100 times smaller than a typical raindrop. If a cloud droplet is in equilibrium with its surroundings, the size of the droplet does not change because the water molecules condensing onto the droplet will be exactly balanced by those evaporating from it. If, however, it is not in equilibrium, the droplet size will either increase or decrease, depending on whether condensation or evaporation predominates” (Ahrens, 2009, p.167). During the flight operations of the Cloud Physics Project, droplet size measurements in convective clouds were done over the ocean in the vicinity of Puerto Rico and over the central United States. (Battan & Reitan, 1955, p.184) The electricity of rain was tested using experimental aircraft during the Army-Navy Precipitation Static Project in Minneapolis, Minnesota, in 1945, in which electrical equipment was developed to measure the charges on raindrops beneath the right wing of a B-17 airplane. (Houghton, 1958, p.16-19) Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or headings unless they are unavoidable.

### B. Classification of Clouds

Clouds play a vital role in many weather and climate processes. A cloud is a form of condensation best described as a dense concentration of suspended water droplets or tiny ice crystals. (Lutgens & Tarbuck, 2014, p.3) “Every time a cloud forms, it warms the atmosphere. For example, within a developing thunderstorm, a vast amount of stored heat energy (latent heat) is released to the air as invisible water vapor condenses into countless billions of water droplets and ice crystals. In fact, for the duration of this storm alone, more heat energy is released inside this cloud that is unleashed by a small nuclear bomb”. (Ahrens, 2009, p.34)

Although ancient astronomers named the major astronomical constellations about 2000 years ago, clouds were not formally identified and classified until the early nineteenth century. According to Ahrens (2009, p. 122), the French naturalist Lamarck (1744-1829) proposed the first

system for classifying clouds in 1802; however, his work did not receive wide acclaim. One year later, in 1803, a cloud classification was introduced by Luke Howard, an English biologist and amateur meteorologist, which was coined with three Latin names: cirrus, cumulus, and stratus, which are still in use today. (Christopherson & Birkeland, 2015, p.208; Grant, 1944, p.35) Howard’s innovative system employed Latin words to describe clouds as they appear to a ground observer, i.e. sheet like cloud stratus (Latin for ‘layer’), a puffy cloud cumulus (‘heap’), a wispy cloud cirrus (‘curl of hair’) and a rain cloud nimbus (‘violent rain’) (Ahrens, 2009, p.123) Simply briefing, two main types of clouds are stratus (‘layer’ in Latin) and cumulus (‘heap’ in Latin). Stratus clouds appear dull, grey, and featureless, whereas cumulus clouds appear bright and puffy like cotton balls. (Christopherson & Birkeland, 2015, p.208, 210) A major distinction between the two is that stratus clouds are in sheets of no great thickness but often of large and unbroken horizontal extent, and cumulus clouds rise to great heights relatively to their horizontal extent, where the vapor in the rising currents condenses in rounded masses separated by blue sky. (Kendrew, 1949, p.180)

Ahrens (2009, p.123) further reports that in 1887, Abercromby and Hildebrandsson expanded Howard’s original system and published a classification with only slight modifications that is still in use today, in which ten principal cloud forms are divided into four primary cloud groups. Each group is identified by the height of the cloud base above the surface: high, middle, and low clouds. The fourth group contains clouds showing more vertical than horizontal development.

In 1896, the procedure for classifying clouds primarily by their shapes and heights was adopted, which later became known as the International Cloud Year, during which observers at meteorological stations around the world were dedicated to identifying cloud types. As a result, ten major cloud types were identified and introduced to the International System of Classification of 1905. (Grant, 1944, pp.35-36) Accordingly, the ten types of cloud, arranged according to their height above the ground, are as follows: “Family A – High clouds (lower level 20,000 feet): 1) Cirrus (Ci)- the feathery ice cloud, 2) Cirrostratus (Cs) – curtains of the coming night, 3) Cirrocumulus (Cc)- mackerel sky. Family B – Middle clouds (upper level 20,000 feet and lower level 6,500 feet): 4) Alto cumulus (Ac) – the herringbone, 5) Altostratus (As) – whirling altostratus. Family C- Low clouds (upper level 6,500 feet and lower level close to the surface): 6) Stratocumulus (Sc) – not necessarily associated with rain 7) Stratus (St) – Lifted fog in a horizontal stratum 8) Nimbostratus (Ns). Family D – Clouds with vertical development (upper level that of cirrus and lower level 1,600 feet): 9) Cumulus (Cu) – The wool-pack or cloud with silver lining 10) Cumulonimbus (Cb) – the thundercloud, shower cloud” (Grant, 1944, p.36). As explained, the international system comprises four families and 10 genera.

Referring to the aforementioned cloud classification, it is apparent that the shape and altitude are the key indicators. Clouds occur in three basic forms: 1) flat, 2) puffy, and 3)

wispy, and in four primary altitude classes of low, middle, high, and clouds vertically developed through the troposphere (lower atmosphere 0-12km). Accordingly, 1) flat and layered clouds with horizontal development are classed as stratiform, 2) puffy and globular clouds with vertical development are cumuliform, and 3) Wispy clouds, usually quite high in altitude and made of ice crystals, are cirroform. (Christopherson & Birkeland, 2015, p.208, 210)

According to Brintjes (1999, p. 808), clouds are further categorized as either continental or maritime, which describes the degree of colloidal instability.

Kendrew (1949, p.180) explains a classification of clouds according to height: 1) High Cloud (cirro), including cirrus, cirro-cumulus, and cirro-stratus, usual level 20,000 to 30,000 feet and up to 50,000 feet near the equator. 2) Middle cloud (alto), alto-cumulus and alto-stratus, usual level 7,000-20,000 feet. 3) Low clouds, stratus, nimbo-stratus, strato-cumulus, cumulus, and cumulo-nimbus with tops up to cirrus level.

Cirrus is a fine weather cloud, too high and tenuous to give rain, and so thin that it appears white, without shadows. It is common in the equatorial belt, moving slowly from the East. Its trails resemble curls of hair (whence the name cirrus), Cirro-Stratus appearing only as a milky of the sky and haloes of the sun or moon. Cirro-cumulus consists of small white cloudlets, separate but usually grouped closely in large sheets or waves. (Kendrew, 1949, p.181-182)

Alto-stratus is thinner in forms and can be recognized by the 'watery' sun or moon visible through it, but this stage soon passes into a thicker or too thick for even a watery sun to be seen. The cloud itself is an almost amorphous grey sheet, dull and uninteresting. Common in all regions, it gives large amounts of steady, persistent rain, at times remarkably heavy. Alto-cumulus is a beautiful, small, rounded cloudlet, white with light grey shadows, often grouped in wave-like lines with an edging of rainbow colors. (Kendrew, 1949, p.182)

Cumulus is a low cloud with beautiful, rounded, cauliflower-like heads, frequently seen in the afternoon sky. In cloud-seeding, cumulus-type clouds are the clouds seeded to precipitate rain. They build up in the warmest hours of the day over the lands, when the condensation of the vapor in the air that rises from heated ground, but are not so common over the oceans. Stratus is a layer form and more or less uniform thickness over large areas, so that it appears amorphous from below. It's dull, grey covering the sky from horizon to horizon. Strato-cumulus usually results from turbulence in cool, damp air. The turbulent air must be in fairly rapid horizontal movement; otherwise, turbulence would not be set up, and consequently the cloud layer tends to assume a widely wave-like form, made visible by lighter and deeper shades of grey. This is one of the commonest types and may overspread the whole sky for days and even weeks together, the persistent gloom constituting a depressing feature in the climate. (Kendrew, 1949, p.183-184)

The term 'nimbo' or 'nimbus' refers to the rain clouds when both stratus and cumulus convert into rain clouds. According to Luke Howard, nimbus means the 'black rain cloud'. (Grant, 1944, p.35) Cumulonimbus is famous as the thundercloud. Upper level equal to that of cirrus, mean lower level 1,600 feet. Heavy masses of cloud rising in the form of mountains, turrets, or anvils, generally surrounded by a sheet or screen of fibrous appearance (false cirrus, tops of cumulus clouds blown off by the storm wind) and having at its base a mass of cloud similar to nimbostratus. (Grant, 1944, p.41)

Further, the prefix 'fracto' (broken) applies to wind-blown clouds, i.e., Fractostratus (Fs), Fractonimbus (Fn): scud of the sailors and Fractocumulus (Fc). Moreover, detached or isolated forms of peculiar forms of clouds were also identified, i.e., Cumulonimbus mammatus (mammato cumulus) (Cm), Altocumulus castellatus (Acc), or scattered cumuliform tufts, Lenticular cloud- existing at all levels from cirrostratus to stratus, and Banner cloud. (Grant, 1944, p.37)

As per the International Atlas of Clouds and the State of the Sky, issued in 1930, the International Commission for the Study of Clouds divided clouds into three main categories: 1) isolated heap clouds: develop vertically and spread out when dissolving, 2) sheet clouds: may be stable or in the process of disintegrating. They may consist of filaments, scales, or rounded masses. 3) more or less continuous cloud sheets: lack stability, being more often than otherwise in the process of formation or growth. (Grant, 1944, p.36)

The International Meteorological Organization in a meeting in Warsaw in 1935 adopted shorter abbreviations which supersede those shown in International Atlas, i.e. Ci, Cc, Cs, Ac, As, Sc, St, Ns, Cu, Cb, Cm, Fs, Fc and Acc. (Grant, 1944, pp. 38-39) On the other hand, the U.S. Weather Bureau, in Circular S, W.B. No 1249 states 'Codes for Cloud Forms and States of the Sky' and in Circular M, W.B. No. 1221 provides 'Instructions to marine Meteorological Observers' in pages 59-60. (Grant, 1944, p.244) These codes were employed by the Weather Bureau when the information was transmitted by radio.

### C. Cloud Development

Clouds form as air rises, cools, and condenses. Therefore, the air needs a trigger to move upward. Accordingly, Ahrens (2009, p.151) explains four mechanisms responsible for the development of the majority of clouds:

Surface heating and free convection (convection and clouds): some areas of the earth's surface better absorb sunlight and become warmer than their surroundings. These 'hot spots' create a hot bubble of air (a thermal) that breaks away from the warm surface and rises, expanding and cooling as it ascends. These are called convective clouds. The vertical development of a convective cloud depends upon the mixing that takes place around its periphery, where the rising, churning cloud mixes cooler air into it, and such mixing is called 'entrainment'. (Ahrens, 2009, p.154)

Forced lifting (uplift) along topographic barriers (topography and clouds): forced lifting along a topographic

barrier is called ‘orographic uplift’. When large masses of air rise as they approach a long chain of mountains, the lifting cools the air, and if the air is humid, clouds form. The clouds produced in this manner are called orographic clouds. On the leeward (downwind) side of the mountain, as the air moves downhill, it warms. This region on the leeward side, where precipitation is noticeably less, is called a ‘rain shadow’, and precipitation occurs on the windward side. (Ahrens, 2009, p.156) As the unsaturated air rises, it cools and reaches its dew point, becoming saturated at 1000m. This level is called the ‘lifting condensation level (LCL)’ (Ahrens, 2009, p.157)

Widespread ascent due to convergence of surface air, also known as convergence, which occurs due to low surface pressure.

**Uplift along weather fronts:** This occurs when warm air is sandwiched between cold air masses, causing it to rise. (Ahrens, 2009, p.151).

Ahrens (2012, p. 151) explains the range of surface heating required for cloud development in these four scenarios: in convection, it seems possible to have the heated surface within a 5km range. In orographic uplift, lifting along topography occurs within a 150km range. In convergence, it can happen within 500km. In lifting along weather fronts, it occurs in the range of 1500km.

#### D. Cloud Seeding Clouds

Cloud seeding cannot make clouds appear out of thin air. It requires existing clouds with specific conditions, i.e., adequate moisture and temperature range to work. Lay audiences often misunderstand it as an on-demand rain switch for any weather condition. On the other hand, not every cloud is suitable for cloud seeding. As per GAO (2024), cloud seeding operations can only enhance precipitation when the right kind of clouds are present, which limits opportunities for success. i.e., ascent by turbulence forms sheets of cloud, mostly Strato-cumulus, not usually massive enough to rain unless reinforced by other processes. (Kendrew, 1949, p.194)

It must also be noted that ‘only a small part of the available moisture in clouds is transformed into precipitation. This fact has prompted scientists and engineers to explore the possibility of augmenting water supplies through cloud seeding. (Bruintjes, 1999, p.805-806) Rain clouds are altostratus, stratus, and stratocumulus, which frequently yield rain or snow, whereas precipitation occasionally reaches the ground from altocumulus and cumulus. (Grant, 1944, p.41) Cumulus and strato-cumulus are known as monsoon clouds.

Convection plays an imperative role in the formation of all types of rain in the tropics, where Convective clouds are cumulus (convective cumulus clouds) and cumulonimbus. ‘Mountains take millions of years to form, while a cumulus cloud can develop into a raging thunderstorm in less than an hour’ (Ahrens, 2012, p. xix). Regarding storm clouds, cloud seeding can only be used to supplement the precipitation in an existing storm. It can’t be used when there are no storm clouds to squeeze additional moisture from, making it impossible to fight wildfires that occur during extremely dry

conditions. It can, however, be used to alleviate drought conditions, which can help mitigate wildfire risk (DRI, 2023)

Mountain barriers are very effective in causing air to rise, forming orographic clouds and heavy rain. Such precipitation is termed orographic rain. ‘Rain may fall on the hills when the lowlands have none, and when it rains on lowlands it almost rains more heavily on the hills’ (Kendrew, 1949, p.189). In contrast, the area of low rainfall on the leeward side of a mountain system is called the rain shadow. (Kendrew, 1949, p.194) ‘Clouds with super-cooled liquid water often form around mountain ranges as the air rising over them quickly cools with the elevation change’ (DRI, 2023)

#### E. Precipitation of Rain

Lutgens and Tarbuck (2013, p. 32) explain the evolution of oxygen in the atmosphere, noting that nearly 3.5 billion years ago, as Earth cooled, water vapor condensed to form clouds, and torrential rains filled low-lying areas, which became the oceans.

The precipitation includes not only rain, snow, and hail but also the ‘ocult’ forms, dew, hoarfrost, and rime, which result in condensation on the surface. (Kendrew, 1949, p.187) Precipitation is actually not rain, but overwhelmingly solid in the main portion of the thunder-cloud. (Houghton, 1958, p.27) Liquid (or solid) cloud particles may grow in size and fall to the surface as precipitation by rain, snow, or hail (Ahrens, 2009, p.90). The largest form of precipitation, hail, often falls during the warmest time of the year. (Ahrens, 2009, p.166) Heavy showers in the afternoons, called ‘April showers’ (Kendrew, 1949, p.188). Cloudy weather does not necessarily mean that it will rain or snow. Although clouds form by condensation, apparently condensation alone is not sufficient to produce rain.

Rain, no matter how produced, either naturally or artificially, be it land, storm, or thunderstorm variety, comes out of the rising and cooling of warm, moist air. 1) Land rain is usually light and occurs in quiet weather. 2) Storm rain, although as a rule its duration is shorter, such rain may last some 24 hours at a single place. It may affect a wide area or cause serious, widespread flooding. ‘Local thunderstorms that last only a few minutes may discharge some 300,000 tons of water on the earth. (Grant, 1944, p.125) 3) Thunder rain happens on a warm summer afternoon when a typical thunderstorm straight overhead is in action, a heavy deluge of rain is to be expected. Thunder rain in summer as it comes crashing down bears no relation to the paths of cyclones, nor to the contours of land. Less than a thousand yards may divide a spot without visible signs of rain from one where an inch or more has fallen. (Grant, 1944, p.126)

Another two types explained by Grant (1944, p.127-128): 1) Cloudbursts are the local thunderstorms lasting only a few minutes of excessively heavy local downpours of rain, but they are of brief duration. 2) A waterspout is a funnel-shaped cloud extending from the underside of an ordinary cumulus cloud, whirling winds from the surface of a lake or ocean. Like tornadoes, waterspouts occur with an approaching cold front and considerable precipitation.

Ahrens (2009, p.187) summarizes eight precipitation types: 1) Drizzle: tiny water drops with diameters less than 0.5mm that fall slowly, usually from a stratus cloud. Fine uniform drops of water whose diameters are smaller than 0.5 mm (which is a diameter about one half the width of the letter “o” on this page) are called drizzle. Most drizzle falls from stratus clouds; however, small raindrops may pass through unsaturated air, partially evaporate, and reach the ground as drizzle. (Ahrens, 2009, p.175) 2) Rain: Most people consider rain to be any falling drop of liquid water. To the meteorologist, however, that falling drop must have a diameter equal to, or greater than, 0.5 mm to be considered rain. (Ahrens, 2009, p.175) 3) Snow: white (or translucent) ice crystals in complex hexagonal (six-sided) shapes that often join together to form snowflakes. 4) Sleet (ice pellets): Frozen raindrops that form as cold raindrops (or partially melted snowflakes) refreeze while falling through a relatively deep subfreezing layer. 5) Freezing rain: super-cooled raindrops that fall through a relatively shallow subfreezing layer and freeze upon contact with cold objects at the surface. 6) Snow grains (granular snow): white or opaque particles of ice less than 1 mm in diameter that usually fall from stratus clouds, and are the solid equivalent of drizzle. 7) Snow pellets (graupel): brittle, soft white (or opaque), usually round particles of ice with diameters less than 5mm that generally fall as showers from cumuliform clouds. They are softer and larger than snow grains. 8) Hail: transparent or partially opaque ice particles in the shape of balls or irregular lumps that range in size from that of a pea to that of a softball. The largest form of precipitation. Large hail has a diameter of  $\frac{3}{4}$  in or greater. Hail is almost always produced in a thunderstorm.

Ahrens (2009, p.175-176) further narrates another three types of rain: 1) Virga: Occasionally, the rain falling from a cloud never reaches the surface because the low humidity causes rapid evaporation. As the drops become smaller, their rate of fall decreases, and they appear to hang in the air as a rain streamer. These evaporating streaks of precipitation are called virga. 2) Shower: If the updraft weakens or changes direction and becomes a downdraft, the suspended drops will fall to the ground as a sudden rain, called a shower. 3) Cloudburst: showers falling from cumuliform clouds are usually brief and sporadic, as the cloud moves overhead and then drifts on by. If the shower is excessively heavy, it is termed a cloudburst.

It is imperative to point out that when rain combines with gaseous pollutants, i.e., oxides of sulfur and nitrogen, it becomes acidic. The burning of sulfur-containing fuels, i.e., coal and oil, releases the colorless gas sulfur dioxide (SO<sub>2</sub>) into the air. When the atmosphere is sufficiently moist, SO<sub>2</sub> may condense into tiny, dilute drops of sulphuric acid. Rain containing sulphuric acid corrodes metals and painted surfaces, and turns freshwater lakes acidic. (Ahrens, 2009, p.10) Acid precipitation means rain or snow with a pH value that is less than the value for uncontaminated rain. (Lutgen & Tarbuck, 2014, p.2) Acid rain, which harms plants and water resources, is becoming a major problem in many industrialized regions of the world. (Ahrens, 2009, p. 176)

#### IV. CLOUD SEEDING TECHNIQUE

Cloud seeding is the process of inducing rainfall or stimulating precipitation through human intervention when the natural hydrological cycle fails. (Bruitjes, 1999, p.809) The Vietnam War is evidence of the USA's attempts to disrupt regional weather patterns through cloud seeding. (Westing, 1984, p.1) It is also technically proven that for successful cloud seeding, ‘Goldilocks’ conditions are required, which occur only within a narrow set of meteorological conditions, specifically in supercooled clouds (those containing water droplets below freezing, usually between -7°C and -20°C). If the atmosphere is too dry or too warm, seeding has no effect.

##### A. Seeding Types

As defined by Lutgens and Tarbuck (2013, p.3), cloud-seeding is the introduction into clouds of particles (most commonly dry ice or silver iodide) for the purpose of altering the cloud's natural development. In fact, some particles are hygroscopic (‘water-seeking’), and water vapor condenses upon these surfaces when the relative humidity is considerably lower than 100%. Ocean salt is hygroscopic, as is common table salt. Whereas others are hydrophobic (‘water-repelling’), i.e., oils, gasoline, and paraffin waxes, and resist condensation even when the relative humidity is above 100 percent (Ahrens, 2009, p.113)

Accordingly, two principal processes account for the majority of the world's raindrops and snowflakes: 1) Warm cloud-seeding and 2) Cold cloud-seeding.

Naturally, clouds with temperatures above freezing at all levels are called warm clouds. In such clouds, precipitation forms by the collision and coalescence process. For example, in tropical regions, where warm cumulus clouds develop to great heights, convective updrafts of at least 1 m/s (and some exceeding 10 m/s) occur. (Ahrens, 2009, p.169)

Warm cloud-seeding (hygroscopic or the collision-coalescence process), involving warmer clouds and falling coalescing droplets. Hygroscopic seeding means using salt particles (NaCl or KCl) to attract moisture and increase droplet size, thereby causing rain. The direct introduction of appropriately sized CCN that can act as artificial raindrop embryos using water sprays, dilute saline solutions, or ground salt is the most common hygroscopic technique. The primary objective of introducing artificial raindrop embryos (salt particles) is to jump-start the coalescence process. In clouds with tops warmer than -15°C (5°F), the collision-coalescence process can play a significant role in producing precipitation. (Ahrens, 2009, p.168) As cloud droplets fall, the surrounding air retards their descent. The amount of air resistance depends on the size of the drop and its rate of fall: the greater its speed, the more air molecules it encounters each second. Large droplets overtake and collide with smaller drops in their path. This merging of cloud droplets by collision is called coalescence. (Ahrens, 2009, p.168) Hygroscopic seeding with salts is, conversely, injected into the base of the cloud warmer to favor condensation, coalescence, and rain. To this end, the injected particles must be more efficient than the CCN already

present in the air, for example, by being more hydrophilic or larger. (SSC, 2023, p.93-94)

Cold cloud-seeding (Glaciogenic or the Bergeron ice-crystal process), in which super-cooled water droplets evaporate and are absorbed by ice crystals that grow in mass and fall (Christopherson & Birkeland, 2015, p.208; Wallace and Hobbs, 2006, p.245-247; Brientjes, 1999, p.813; ScienceDirect Topics). In other words, this involves improving the cloud's ability to produce precipitation by adding tiny particles called ice nuclei (particles with an ice crystal structure that water needs to freeze). These nuclei help the cloud produce precipitation by freezing supercooled liquid water (SLW), which are cloud droplets that remain liquid at temperatures below 32°F. (Atmospheric Resource Board)

Glaciogenic seeding involves using silver iodide and dry ice to cause precipitation, also known as the ice-nucleating method, which is two-fold: 1) Static cloud seeding means the use of silver iodide for ice crystal formation leads to snow or rain. 2) Dynamic seeding increases vertical air currents and enhances the ability to produce rain. 'Dynamic seeding focuses on seeding super-cooled clouds with large enough quantities of ice nuclei or coolant to cause rapid glaciation of the cloud'. (Brientjes, 1999, p.812-813) This was first tested by Simpson et.al. (1967). The ice-crystal or Bergeron process (after the Swedish meteorologist Tor Bergeron, who proposed that essentially all raindrops begin as ice crystals) of rain formation is extremely important in middle and high latitudes, where clouds extend upward into regions where the air temperature is well below freezing, referred to as supercooled. (Ahrens, 2009, p.169) Just as liquid cloud droplets form on condensation nuclei, ice crystals may form in subfreezing air on particles called ice nuclei. (Ahrens, 2009, p. 170) According to Rosenfeld & Farbstein (1992), desert dust contains more ice nuclei. The idea behind cold cloud seeding is to first identify clouds with an ice-to-droplet ratio that is too low, and then add sufficient artificial ice nuclei to bring the ratio to about 1:100,000. However, it should be noted that the natural ratio of ice nuclei to cloud condensation nuclei in a typical cold cloud is about 1:100,000, just about optimal for producing precipitation. Glaciogenic seeding using AgI or dry ice can also be used in the upper, colder part of a convective cloud with similar objectives. (SSC, 2023, p.93-94)

According to Brientjes (1999, p.807-809), precipitation growth can occur through coalescence, the ice process, or a combination of both. His analysis indicates that when cloud tops reach temperatures colder than 0°C, ice forms and can lead to precipitation. Conversely, when cloud tops are warmer than 0°C, precipitation can develop via coalescence. Based on this, it is clear that in Brientjes's classification, he refers to coalescence as the warm or hygroscopic method, and ice-developed precipitation as the cold or glaciogenic method.

The first mandatory ingredient in any seeding project is the presence of clouds, as seeding does not generate clouds. Ahrens (2009, p. 173) explains that the primary goal in many cloud-seeding experiments is to inject (or seed) a cloud with small particles that act as nuclei, so that cloud particles grow large enough to fall to the surface as precipitation. Hence,

meteorological conditions and cloud properties play a key role in the success of cloud-seeding-induced precipitation.

In addition to the four types of cloud developments discussed in Section 3.3, most of the studies to date were focused on these two typical cloud systems with reference to cloud-seeding: (1) Orographic clouds (induced by a mountain slope), mainly in winter and in the mid-latitudes. Glaciogenic seeding of wintertime orographic clouds is realized by introducing 'ice nucleating particles' (INP) in a region where a humid air mass rises along a mountain slope, and thus cools down. In this process, super-cooled liquid water droplets are formed and eventually freeze when they reach sufficiently cold conditions, whereby seeding the cloud with, e.g., AgI, ice particles can be formed at higher temperatures (-5°C) and thus at an earlier stage in the orographic process (Flossmann et al. 2019; Tessendorf et al. 2019; French et al. 2018). AgI exhibits a lattice structure similar to that of ice, which favors the freezing of supercooled droplets. This aims to accelerate growth and increase snowfall on the mountains. (2) Convective clouds form in summer over mid-latitude regions or at any season in tropical regions. In convection clouds, the vertical motion (and cooling) is not due to topography but to elevated ground temperature. Seeding can also increase the buoyancy of the cloud by releasing latent heat as supercooled liquid droplets freeze. (SSC, 2023, p.93-94)

Further, as often observed in literature, seeding types can be twofold: randomized and targeted (control-target). Cloud-seeding operations can be on randomly selected days or tenures, or, in contrast, on well-planned, targeted terrains, clouds, and days of the season. In addition, some texts emphasize the terms 1) Static seeding: using silver iodide for ice-crystal formation, which leads to rain or snow, and 2) Dynamic seeding: which increases vertical air currents and enhances the ability to produce rain.

As stated above, cloud seeding is not all about rainmaking. Though this article is limited to rain-making, making it snow is also a feasible technique. In 2020, the ground-breaking study of the SNOWIE Project used 'advanced radar and cloud-measuring technology to show that cloud-seeding coaxed moisture out of super-cooled clouds, producing enough snow to fill 282 Olympic-sized swimming pools over approximately two hours'. (DRI, 2023)

### B. Cloud Seeding Agents

Lay audiences may not grasp how chemicals operate at the microphysical level. Therefore, it is important to evaluate the seeding substances and their specific roles.

As explained by Wallace & Hobbs (2006, p. 248), the material suitable for seeding cold clouds was first discovered in July 1946 during Project Cirrus, which was carried out under the direction of Irving Langmuir. (Refer note 6). Thus, cloud seeding began with the discoveries of Schaefer (1946) and Vonnegut (1947) that supercooled liquid water could be converted to ice crystals using either dry ice or silver iodide.

Silver iodide (AgI): a glaciogenic agent whose crystalline structure promotes ice nucleation in supercooled

clouds. Silver iodide's crystal structure is similar to that of ice, which can transform supercooled water droplets into freezing and growing larger, but this requires an understanding of ice nucleation and atmospheric microphysics. Silver iodide causes ice crystals to form in two primary ways: 1) Ice crystals form when silver iodide crystals come in contact with supercooled liquid droplets. 2) Ice crystals grow in size as water vapor deposits onto the silver iodide crystal. (Ahrens, 2009, p.173) During Operation Popeye in the Vietnam War, silver iodide and lead iodide were dispersed from aircraft, and the operation reportedly increased rainfall by 30%. (Fleming, 2010) Moreover, potassium iodide (KI), similar to AgI, acts as an ice nucleus. (National Oceanic and Atmospheric Administration, 2014) However, although many artificial ice-nucleating materials are now known (e.g., lead iodide, cupric sulfide) and some organic materials (e.g., phloroglucinol, methanal) are more effective as ice nuclei than silver iodide, silver iodide has been used in most cloud seeding experiments. (Wallace & Hobbs, 2006, p.249)

Dry ice (solid CO<sub>2</sub>): extremely cold pellets that freeze super-cooled droplets and create ice crystals quickly (glaciogenic). (Kopp, 1983) Silver iodide is much easier to handle than dry ice, since it can be supplied to the cloud from burners located either on the ground or on the wing of a small aircraft. Although other substances, such as lead iodide and cupric sulfide, are also effective ice nuclei, silver iodide remains the most commonly used substance in cloud-seeding projects. (Ahrens, 2009, p.173) Since the discovery of glaciogenic materials more than 80 years ago, silver iodide and dry ice remain the most widely used cloud-seeding materials in the world (Bruitjes, 1999, p. 809). Therefore, seeding with hygroscopic material has usually appeared less attractive.

Liquid Porphane (or other expanding hydrocarbon flares): generates many small ice crystals when it rapidly expands or cools in the cloud. Used in some aerial or rocket seeding systems. (United States Patent, 1986)

Hygroscopic salts (i.e. sodium chloride, calcium chloride, ammonium nitrate, urea): use for warm cloud hygroscopic seeding as they attract water, grow into large droplets and promote coalescence (rain formation) (Silverman & Sukarnjanaset, 2000) South Korea has analysed the powder type hygroscopic materials i.e. sodium chloride (NaCl) and calcium chloride (CaCl<sub>2</sub>) (Kim et al, 2025) in cloud-seeding using an experimental chamber. Further, hygroscopic flares/powdered salt dispersals/ engineered salt particles or flares designed to produce large droplets in convective (warm) clouds. (U.S. Government Accountability Office, 2024; DWR, 2023)

Biological ice-nucleating agents, i.e., *Pseudomonas syringae* or extracted proteins, have been historically and experimentally investigated as ice nuclei and thus are not commonly used as operational agents. (ScienceDirect Topics)

### C. Modes of Cloud Seeding

During the latter part of the decade, 1980-1990, scientific activity in cloud seeding remained subdued, largely

due to a lack of new findings. However, the early decade of 1990-2000 witnessed many advances in airborne instrumentation, radars, flares, and software. At present, the modus operandi of cloud seeding seems to be being replaced by the latest technology: AI-driven drones. As a result, instead of the traditional aerial seeding method using manned aircraft, countries currently tend to use drones. In this backdrop, the various modes of seeding and dispersion methods in cloud-seeding use both at experimental and operational levels can be categorized as follows:

#### ➤ *Aerial Aircraft Seeding:*

This mode of cloud seeding involves aircraft-based dispersion of agents. The advantages are high precision and the ability to target specific cloud formations. It is the most common method of cloud-seeding where specially equipped aircraft disperse seeding agents directly into or above target clouds, i.e. base-seeding (also known as updraft treatment at cloud base) requires the seeding agent be transported by the cloud's updraft which takes longer time to witness results, in comparison, direct injection at cloud tops involves flying in-cloud and working at higher altitudes. (Atmospheric Resource Board) In other words, aircraft releases particles at specific cloud altitudes either into the cloud base (for warm clouds) or near the super-cooled regions (for cold clouds to stimulate condensation or ice nucleation). Research indicates that cloud seeding from aircraft platforms is more effective than other methods. (Wehbe et al., 2021). Aircraft operations allow for precise targeting and can achieve significant increases in precipitation, with studies showing up to 2-3-fold increases in precipitation flux depending on seeding rates (Tontilla et al., 2021).

This method is widely used in the United States, India, China, the United Arab Emirates, and many other countries. It was reported that the UAE's operational program using aircraft achieved an average 23% increase in annual surface rainfall over seeded areas (Wehbe et al, 2021). Operational Scale Economics: Large-scale operations demonstrate economic viability. The UAE's decade-long operational program represents a substantial investment in aircraft-based seeding, with documented increases in precipitation (Wehbe & Griffiths, 2023). In Thailand, a randomized warm-rain enhancement experiment carried out during 1995-1998 in the Bhumibol catchment area in northwestern Thailand used King Air 350 cloud-physics aircraft. (Silverman and Sukarnjanaset, 1999, p.1160) Russian operations have utilized up to 12 aircraft for weather protection operations, indicating the scale of investment required for comprehensive aircraft-based programs (Korneev et al, 2022) Cloud seeding in North Dakota is conducted via airborne release of silver iodide or dry ice into a convective cloud marked as potentially hail producing (glaciogenic seeding or by direct injection from the top of a cloud). (Knowles & Skidmore, 2021, p.886)

It is imperative to point out that in aerial seeding, release of agents could be executed in three ways: 1) Physical drop, 2) flares burn-in-place (end burning flares), or 3) flares ejectable (ejection flares). These modes suggest controlled and sustained release of seeding materials.

During cloud-seeding experiments in Sri Lanka in 2019, the physical drop of dry ice was the aerial seeding method used. (Fernando, 2025) Jung et al (2022) commented on flares dispersion that dispersion methods for Agl seeding are (1) aircraft-based acetone burners or burn-in-place flares, (2) flares ejected from aircraft at altitudes higher than the region that contains super-cooled droplets. In hygroscopic seeding of NaCl or similar salts, a widely used technique is aircraft-based micro-powder dispersion and flares (burn-in-place or ejectable) (SSC, 2023, p. 94). Flares containing silver iodide or hygroscopic salts are burned either on aircraft wings or from the ground to release particles into cloud layers. The combustion of flares produces fine aerosol particles that are carried into the target cloud by natural updraft.

According to the most recent review of global precipitation enhancement activities conducted by the WMO Expert Team on Weather Modification, cloud seeding from aircraft platforms is generally considered more effective than other techniques, such as ground-based generators, customized rockets, and artillery shells. (Hosari et al., 2021, p.2; Jung et al., 2022, p.2)

#### ➤ *Ground-Based Seeding:*

Ground-based seeding mechanisms include ground-based acetone burners, automatic & remote based generators, manual generators, and flare trees. There is also a possibility that methods such as flares, artillery shells, and rockets also fall under this category if launched from the ground. Ground-based generators release silver iodide smoke or hygroscopic aerosols, which are carried into clouds by air currents. The seeding agents rise with the updrafts to the cloud base, enhancing condensation or ice crystal formation. Used in mountainous regions, i.e., Colorado, Israel, and China, where updrafts naturally lift the particles.

In practical applications, ground-based systems appear most suitable for continuous operations in mountainous terrain, where generators can be strategically positioned. The Idaho Power study demonstrated effective coverage within 70 km of ground sources (Fisher et al, 2018). Aircraft-based seeding offers flexibility for targeting specific storm systems but requires significant operational infrastructure. Compared with aerial seeding, ground-based seeding systems offer operational advantages in deployment and maintenance costs. Studies show that silver enrichments were detected at 88% of cases involving ground-based generators within 70 km of sources, compared to no detectable signatures from aircraft seeding in the same study. (Fisher et al., 2018) They can even operate continuously during suitable weather conditions and require less specialized personnel than aircraft operations (Korneev et al, 2022). The main advantages are low operational costs and 24-hour capability, even though less precise than aerial methods.

#### ➤ *Rocket Seeding and Artillery Shells:*

Rockets (rain rockets) loaded with seeding agents are launched into clouds, where they detonate or release silver iodide or salt particles at desired altitudes. The released chemicals act as cloud condensation or ice nuclei, encouraging raindrop formation. Commonly used in China

and Thailand, especially during the monsoon seasons. Compared to aircraft seeding, this is faster and less weather-dependent. Suitable for mountainous or dangerous terrain. Rocket Delivery Systems provide precise altitude and timing control. The temporally controllable weather-modification rocket can operate at altitudes of 500-5500 m, with seeding initiation times ranging from 2 to 26 seconds. These systems can launch 48 catalyst bullets within 0.8 seconds, enabling both concentrated and continuous seeding operations (Dong et al, 2024).

In fact, the contemporary rocket seeding in weather modification is categorized into line seeding and spatial seeding. “Line seeding rockets have fixed seeding start times set at the time of production, and the seeding height varies mainly with the launch angles of the rocket launcher, with a relatively limited adjustable range of seeding altitudes. At present, the commonly used line seeding rocket has a seeding time of 15–30 s and a maximum launch altitude of 6000–8000 m. After the rocket is launched, the catalyst burns inside the rocket body. After seeding, it spreads along the rocket's flight path, forming a long, linear silver iodide aerosol band in the air. For spatial seeding rockets, although the seeding start time can be set before launch, the adjustment range is currently limited to 3–12 s. With a launch angle of 55°, the seeding start height is approximately 2000-3200 m, and seeding operations cannot be interrupted once started (Dong et al., 2024, p. 5552). These two techniques perform seeding operations on variable clouds using fixed settings in rockets.

Recent articles from China reported the development and preliminary testing of a temporally controllable weather-modification rocket with spatial seeding capability, featuring an electronically fuse-controlled intelligent ignition system with eight ignition-tube outputs. Additionally, carrier wave communication technology is incorporated to set the seeding time for eight sets of ignition tubes. (Dong et al., 2024, p.5551) Therefore, compared with other methods, rocket seeding is found to be easy and cost-effective.

Artillery-based cloud seeding was explored and implemented primarily by state actors in wartime weather modification, i.e., Cold War experiments, and it remains documented as an experimental and regional method rather than a dominant approach. In parts of Eastern Europe and the former Soviet Union, artillery rockets and shells were reportedly used in hail-suppression campaigns to protect agriculture by altering hail formation rather than increasing rainfall.

#### ➤ *Drone-Based Seeding:*

Drone-Based Methods (UAVs) represent an emerging technology for cloud seeding. Drones equipped with seeding canisters or flares disperse particles at precise altitudes and coordinates. The drones release chemicals such as silver iodide or calcium chloride directly into the cloud formation, often guided by AI or remote sensing data. The UAE's National Center of Meteorology and India's Agni Aero Sports have tested drones for cloud seeding. Jung et al. (2022) report the increasing use of UAVs to spray calcium

chloride for cloud seeding in Korea, resulting in 0.5mm of rain.

The technology offers advantages in terms of operational safety and reduced personnel requirements compared to manned aircraft. The main advantages of this mode are that it is cost-effective and safe, and that it allows operation in hazardous weather where manned aircraft are unsuitable.

#### *D. Meteorological Equipment Involved in Cloud Seeding*

In the discourse on the modus operandi of cloud seeding, this article finds it imperative to draw the attention of lay audiences to the meteorological equipment required for cloud seeding. Radiosonde, rawinsonde, laser-beam ceilometer, Doppler radar, and adiabatic charts are mandatory for cloud seeding, with a rain gauge used to measure rainfall.

**Radiosonde:** This is an instrument that measures the vertical profile of air temperature in the atmosphere up to an elevation sometimes exceeding 30km (100,000ft). (Ahrens, 2012, p.15) 'It is a small, lightweight box equipped with weather instruments and a radio transmitter, which is attached to a cord that has a parachute and a gas-filled balloon tied tightly at the end. As the balloon rises, the attached radiosonde measures air temperature with a small electrical thermometer (a thermistor) located just outside the box. The radiosonde measures humidity electrically by sending an electric current across a carbon-coated plate. Air pressure is obtained by a small barometer located inside the box. For radiosondes, special surface-tracking equipment may also be used to provide a vertical profile of winds. (When winds are added, the observation is called a rawinsonde.) All of this information is transmitted to the surface by radio. There, a computer rapidly converts the various frequencies into temperature, pressure, and moisture values. When plotted on a graph, the vertical distribution of temperature, humidity, and wind is called a 'sounding'. Eventually, the balloon bursts and the radiosonde returns to earth, its descent being slowed by its parachute. At most sites, radiosondes are released twice a day, usually at times corresponding to midnight and noon in Greenwich, England. Releasing radiosondes is an expensive operation because many instruments are never retrieved, and those that are often in poor working condition. To complement the radiosonde, modern satellites are providing scientists with vertical temperature profiles in inaccessible regions (Ahrens, 2012, p.16; Lutgens & Tarbuck, 2014, p.40)

A rawinsonde is tracked by radio-location devices to obtain data on upper-air winds. Observations where winds aloft are obtained are called "rawinsonde" observations. (Lutgens & Tarbuck, 2014, p.9, 40)

**Laser-beam Ceilometer:** In cloud seeding, it is usually important to have a good estimate of cloud base height; particularly at lower elevations, an aircraft cannot operate safely without accurate cloud height information. Ceiling balloons (a small balloon filled with a known amount of hydrogen and helium) can measure the height of clouds. The ceiling is determined by measuring the time it takes for the

balloon to reach the lowest cloud layer. i.e, if the balloon rises 125m (about 400ft) each minute, and it takes three minutes to enter a broken layer of stratocumulus, the ceiling would be 375m (about 1200ft) (Ahrens, 2009, p.132) Also, at night, ceiling balloon observations can be made simply by attaching a small battery-operated light to the balloon. For many years, the rotating-beam ceilometer provided information on cloud ceiling, especially at airports. This instrument consists of a ground-based projector that rotates vertically from horizon to horizon. As it rotates, it emits a powerful light beam that travels along the base of the cloud. Most rotating-beam ceilometers have been phased out and replaced with laser-beam ceilometers, in which the transmitter emits intense pulses of infrared radiation that strike the cloud base, and a portion is reflected to the receiver. The time interval between pulse transmission and its return from the cloud determines the cloud-base height.

**Doppler radar:** In atmospheric science, radar is used to examine the interior of a cloud, much like physicians use X-rays to examine the human body. "During the 1990s, Doppler radar replaced the conventional radar units that were put into service shortly after World War II. Doppler radar is like conventional radar in that it can detect areas of precipitation and measure rainfall intensity. Essentially, the radar unit consists of a transmitter that sends out short, powerful microwave pulses. When this energy encounters a foreign object (called a 'target'), a fraction of the energy is scattered back toward the transmitter and is detected by a receiver. The returning signal is amplified and displayed on a screen, producing an image (echo) of the target. The elapsed time between transmission and reception indicates the target's distance". (Ahrens, 2012, p.188) The next improvement for Doppler radar is polarimetric radar. This form of Doppler radar transmits both vertical and horizontal pulses, making it easier to determine whether falling precipitation is rain or snow.

An adiabatic chart is a graph that shows how various atmospheric elements change with altitude. It is a chart that indicates pressure (mb), temperature (C), and Altitude (km and ft). Slanted solid red lines in the chart are called 'dry adiabats', while sloping dashed blue lines are called 'moist adiabats'. (Aherens, 2012, p.158)

A rain gauge is the instrument that measures rain. It indicates rain by collecting it in a suitable receptacle and storing it until it can be measured, usually once a day. The instrument is usually placed in an open situation well away from the shelter of trees or other objects, but not so exposed that eddies around the gauge in strong winds prevent some rain or snow from entering. The rim is 1 foot above the ground at British stations, and in North Germany, a gauge 1 meter high catches, on average, about 8% of the precipitation. At the Radcliffe Observatory, Oxford, a gauge on the tower, 112 feet high, caught on average 30%' [Emphasis added] (Kendrew, 1949, p.175). Measurement of rain is the depth in inches or mm of the resulting layer of water, without loss by run-off, percolation, or evaporation. It is also said that a rain gauge cannot be used on ships at sea.

(Kendrew, 1949, p.174). An amount of rainfall less than one-hundredth of an inch is called a 'trace'. (Ahern, 2012, p.186)

## V. CONCLUSION

In a nutshell, cloud seeding is a weather modification technique that requires mastery of a myriad of topics in cloud physics, cloud studies, meteorology, atmospheric physics, and chemistry. Due to the very reason that the *modus operandi* of cloud seeding explained in existing literature is complicated in facts and terminology and finds it challenging to be understood by the lay audiences, i.e., public, policymakers, media, and local stakeholders, it lacks a solitary work in explaining the overall cloud seeding mechanism alongside the scientific inquiry. On the other hand, as the procedural governance of cloud seeding transcends inter-disciplines, i.e., legal, economic, and political, it seems the need of the hour to elucidate its technique in simple language to raise awareness of the public at large and bolster the policy making with the involvement of legal, economic, and political experts from non-scientific backgrounds. Therefore, the knowledge deficit model, using a qualitative approach, was employed to meet the objective of this article: to elaborate on the *modus operandi* of cloud seeding for larger, non-scientific stakeholders.

Accordingly, Section 2 provided a preface to exploring the earth by discussing atmospheric layers and hydrologic cycle as the lack of a sound knowledge of atmosphere and hydrosphere of the Earth, disqualify the non-scientific audiences in understanding the *modus operandi* of cloud-seeding, as the atmosphere and hydrosphere is imperative to understand the basis behind the science and techniques of cloud seeding, as they stabilize weather and the water cycle of the earth by enabling cloud formation, precipitation and wind circulation. The Earth's atmosphere being the gaseous mass blanketing the earth, as a protective shield, that is held in place by earth's gravity is generally divided into five vertical layers based on the temperature variations i.e. troposphere up to about 12 km, stratosphere 12-50km, mesosphere 50-85 km, thermosphere about 85-600km and exosphere the outermost layer extending from 600km to gradually fading into outer space. Another division categorizes the atmosphere into two layers based on the composition, i.e., the homosphere, where the air remains uniform, 78% nitrogen and 21% oxygen, and the region above the thermosphere is identified as the heterosphere. However, to understand cloud seeding, the most important layer is the troposphere, where clouds develop vertically. Next, the hydrologic cycle is equally vital for understanding water in the atmosphere, cloud formation, and rain. It begins with evaporation, in which the sun evaporates water from the oceans to form clouds, and the shifting status of water molecules is driven by condensation and saturation.

Section 3 provided background on the subject by evaluating cloud formation, classification, development, seeding, and precipitation. Clouds form when air at some height above the surface is cooled, and, if condensation continues, the particles coalesce into drops or ice crystals large enough to fall as precipitation. Cloud condensation

nuclei (CCN) are the core cloud-physics concept relevant to cloud seeding for lay audiences in rainmaking. Clouds are classified based on their shape and different altitudes in troposphere (lower atmosphere 0-12km) generally as ten types of: Family A: High clouds (lower level 20,000 feet): 1) Cirrus (Ci)- the feathery ice cloud, 2) Cirrostratus (Cs) – curtains of the coming night, 3) Cirrocumulus (Cc)- mackerel sky. Family B – Middle clouds (upper level 20,000 feet and lower level 6,500 feet): 4) Altopumulus (Ac) – the herringbone, 5) Altostratus (As) – whirling altostratus. Family C- Low clouds (upper level 6,500 feet and lower level close to the surface)6) Stratocumulus (Sc) – not necessarily associated with rain 7) Stratus (St) – Lifted fog in a horizontal stratum 8) Nimbostratus (Ns). Family D – Clouds with vertical development (upper level that of cirrus and lower level 1,600 feet): 9) Cumulus (Cu) – The wool-pack or cloud with silver lining 10) Cumulonimbus (Cb) -the thundercloud, shower cloud. In cloud development, four mechanisms are responsible: surface heating and free convection, forced uplift along topographic barriers, convergence of surface air due to low surface pressure, and uplift along weather fronts. It was also evident in the discourse that cloud seeding cannot make clouds appear out of thin air, nor is every cloud capable of seeding. Out of several types, it is apparent that altocumulus and cumulus clouds are the potential rain-making clouds, despite diverse meteorological terminology used to explain the ways rain meets the surface earth via either cloudbursts or waterspouts or drizzle or rain, snow, sleet, freezing rain or snow grains or snow pellets or hail or virga or showers.

Section 4 of the article emphasized cloud-seeding techniques by discussing seeding types, cloud-seeding agents, modes of cloud-seeding, and, lastly, the meteorological equipment involved in cloud-seeding. The explanation of seeding types has been presented in two ways: warm cloud seeding (hygroscopic or collision-coalescence process) and cold cloud seeding (glaciogenic or Bergeron ice-crystal process). Further, randomized, control-target, static, and dynamic seeding have also been summarily explained. In the dialogue on cloud-seeding agents, hygroscopic salts used in warm cloud seeding, silver iodide and dry ice, famously used in cold cloud seeding, and liquid propane and biological ice-nucleating agents are discussed in detail. Then, the modes of cloud seeding, namely, aerial aircraft seeding, ground-based seeding, rocket seeding, artillery shell seeding, and drone-based seeding, at both operational and experimental levels, are analyzed with relevant country practices. Moreover, the meteorological equipment used in cloud seeding, i.e., radiosonde, rawinsonde, laser-beam ceilometer, Doppler radar, and adiabatic charts, is described, and a lay audience description of a rain gauge is provided.

Due to a lack of basic scientific understanding of cloud seeding, the public, policymakers, the media, and local stakeholders are susceptible to rumors. Additionally, an evidence gap exists regarding how to translate technical exposure assessments into locally meaningful messages, and about the variability in measuring effectiveness, as technology often seems unreliable or contentious to the

public. Without clear communication about who benefits and who loses, cloud seeding also faces political resistance. In these circumstances, the objective of this article was to bridge the knowledge gap between cloud-seeding science and lay audiences; the aforementioned overview of the modus operandi of cloud-seeding in simple language, as well as the explanatory version, seemed a success as conceived by the broader non-scientific stakeholders.

➤ *Notes:*

- 39 country list: GOA (2024, p.32-34) has provided a non-exhaustive list of 39 countries reportedly engaged in any of cloud-seeding from 2020 to 2024; Argentina, Australia, Austria, Bulgaria, Burkina Faso, Canada, Chile, China, Ethiopia, France, Germany, Greece, India, Indonesia, Iran, Israel, Japan, Malaysia, Mali, Mexico, Moldova, Mongolia, Morocco, Niger, North Korea, Oman, Pakistan, Panama, Philippines, Romania, Russia, Saudi Arabia, Senegal, South Korea, Spain, Switzerland, Thailand, United Arab Emirates, Zimbabwe.
- 56 country list: The most active nation in the field is, by far, China, and then the USA. Among other active countries, great efforts are nowadays deployed by the United Arab Emirates, Russia, Australia, India, Japan, Iran, Israel, South Korea, and Thailand (SSC, 2023, p.91)
- Drogue stabilization means using a drogue (a small parachute or cone-shaped device) to slow down an object and keep its direction steady, preventing uncontrolled tumbling or spinning, common in boating (storm drogues to control waves) or aerospace (stabilizing bombs, ejection seats, or spacecraft during descent). It essentially acts as a drag device to manage speed and orientation in challenging conditions.
- Lapse rate: The rate at which the air temperature decreases with height is called the temperature lapse rate. The average (or standard) lapse rate in this region of the lower atmosphere is about 6.5°C for every 1000 m or about 3.6°F for every 1000 ft rise in elevation. Keep in mind that these values are only averages. Occasionally, the air temperature may actually increase with height, producing a condition known as a temperature inversion. So the lapse rate fluctuates, varying from day to day and season to season. (Ahrens, 2012, p. 12)
- Dew point (100% relative humidity): if unsaturated air is cooled, a temperature is reached at which the vapor present is all that it can normally contain; this is the dew point. If the atmosphere is cooled below the dew point, the excess vapor condenses into minute drops of water or crystals of ice, so small at first that they float as fog or cloud. (Kendrew, 1949, pp.178,179)
- Cloud-seeding agents' history: One of Langmuir's assistants, Vincent Schaefer, observed in laboratory experiments that when a small piece of dry ice (i.e., solid carbon dioxide) is dropped into a cloud of supercooled droplets, numerous small ice crystals form, and the cloud is glaciated quickly. As a result, the first field trials using dry ice were made in Project Cirrus on 13 November 1946, when about 1.5 kg of crushed dry ice was dropped along a line about 5 km long into a layer of a super-

cooled altocumulus cloud. Snow was observed to fall from the base of the seeded cloud over a distance of about 0.5 km before evaporating in the dry air. When a cloud is oversaturated, it is completely converted into ice crystals (i.e., glaciated). This technique is used to clear supercooled fog at several international airports. Following the demonstration that super-cooled clouds can be modified by dry ice, Bernard Vonnegut, who was also working with Langmuir, began searching for artificial ice nuclei. An examination of crystallographic tables revealed that silver iodide fulfills this requirement. Subsequent laboratory tests showed that silver iodide could act as an ice nucleus at temperatures as high as 40 °C. Thereby, the seeding of natural clouds with silver iodide was first tried as part of Project Cirrus on 21 December 1948. Pieces of burning charcoal impregnated with silver iodide were dropped from an aircraft into about 16 km<sup>2</sup> of super-cooled stratus cloud 0.3 km thick at a temperature of 10 C. The cloud was converted into ice crystals by less than 30g of silver iodide. (Wallace & Hobbs, 2006, p.248)

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