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CLOUD SEEDING TECHNOLOGY, A FEASIBLE ALTERNATIVE WATER SOURCE FOR THE CARIBBEAN?

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ABSTRACT: Demands for fresh water in the Caribbean region are increasing due to expanding populations and periodic droughts. Potential global warming impacts are uncertain but may lead to decreased rainfall in the Caribbean in the future. Typical responses to shortfalls in water supplies often include: 1) construction of water storage facilities, 2) water conservation, 3) transfer of water from agriculture to municipal uses, and 4) desalinization (if the area of interest is boarded by an ocean). Another potential source of additional fresh water, cloud seeding, is an alternative that is less commonly considered. Cloud seeding involves the placement of different types of seeding agents into appropriate clouds to bring about a change in the microphysics of the clouds to create a desired response. Cloud seeding can be attempted to increase precipitation or decrease hail. Precipitation augmentation programs are conducted to increase winter snowfall in mountainous areas or to increase rainfall over croplands or water catchment areas. Typical seeding agents include silver iodide and certain types of hygroscopic salts. Winter clouds can be seeded from ground-based "generators" and/or aircraft. Summer clouds are typically seeded using aircraft. Various professional society statements concerning the efficacy of precipitation augmentation programs indicate approximately 5-15% increases can be achieved from well designed and conducted programs. Research oriented as well as operational precipitation augmentation programs have been conducted in and near the Caribbean with positive indications. Towering Cumulus, one type of rain producing cloud that frequently occurs in the Caribbean, is one that is targeted in programs currently being conducted in numerous locations worldwide. The success of these programs is a function of several factors, which include: 1) the frequency of occurrence of "seedable" clouds, 2) the timing and duration of these seeding opportunities, 3) the meteorological conditions associated with these clouds, 4) the location, size, and topography of the desired treatment area, 5) logistical considerations (locations of airports, airport operation periods, aircraft maintenance facilities, air traffic control considerations, etc.), and 6) available weather information, program equipment and experience of the people conducting the program.
Key Terms: Cloud seeding, weather modification, precipitation augmentation.

INTRODUCTION AND BACKGROUND

"Little did Dr. Vincent Schafer realize, while working in a General Electric laboratory in 1946, that he would stumble upon the first scientific indication that man might be able to beneficially modify clouds. Dr. Schaefer was doing research on a hot summer day and cold temperatures were required for his experimentation. He was using a chest type deep freezer for his experimentation. He decided to lower the temperature further by placing a chunk of dry ice into the deep freeze. When he did so, he noticed an unexpected reaction. While working over the open freezer, his breath had created a small cloud of "supercooled" (colder than freezing) water droplets. These droplets appeared as a sort of haze in the freezer when light was shone through them. Introducing dry ice caused the water droplets to freeze due to the very cold temperature of the dry ice. They froze, forming tiny ice crystals that scintillated in the light. Dr. Schaefer's serendipitous discovery demonstrated that "supercooled" cloud water droplets (common in clouds) could be artificially induced to freeze. This classic experiment is easily replicated and is often demonstrated to students and other interested individuals.

There are some famous photos taken in the 1940's and 50's where Dr. Schaefer flew in an airplane equipped to drop dry ice particles into "supercooled clouds". Ice crystals formed via the "seeding" grew into snowflakes which fell to the ground, leaving a hole in the seeded cloud deck. Figure 1 provides an example of one of these early photographs. Further research was conducted on different types of particles that might also cause "supercooled" water droplets to freeze on them. Silver iodide was identified as an excellent particle to cause such freezing, and it remains the most widely used cloud seeding agent for seeding cold (below freezing) clouds.

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Figure 1 Effects of Seeding Alto-Stratus Clouds Over Green Bay, Labrador: 45 Minutes after Seeding with Dry Ice

These developments were greeted with enthusiasm in the 1950's, with a number of research programs being conducted in the Unites States and several other countries, to determine if precipitation could be increased through "cloud seeding." There were mixed results from these programs and those that followed in the 1960's though the 1990's. The difficulties were a result of a number of factors including the complex cloud interactions involved, seeding coverage variability, short experimental period length, and large precipitation variability that can mask the seeding effects. Some disillusionment developed in the scientific community regarding whether cloud seeding "worked" and research in this field declined to near zero in the latter 1990's.

The acid test of whether a seeding experiment was increasing precipitation became a question of whether the indicated results were "statistically significant". The model of randomized trials as used in pharmaceutical testing had been exported to the atmosphere in an attempt to "prove" that cloud seeding worked in many of these research experiments. A 5% statistical significance level was written into the design of weather modification research programs. Attaining a 5% significance level would indicate that there was only a 5% chance that the experimental results would randomly occur without the cloud treatment or stated differently, 95% confidence that observed differences were due to seeding. A number of such research programs had indications of positive seeding results, but these results were rejected by some purists because the 5% significance level was not obtained and these pioneering and positive experiments were unfortunately and unjustly labeled as failures." The preceeding from Griffith, 2010.

ABBREVIATED CLOUD SEEDING THEORY

Clouds form when the atmosphere reaches saturation, that is a relative humidity of 100%. This saturated condition causes water vapor to condense on nuclei forming cloud droplets. These nuclei, which may be small particles like salts formed through evaporation off the oceans, are known as "cloud condensation nuclei." Clouds can be composed of water droplets, ice crystals or a combination of the two. Clouds that are entirely warmer than freezing are sometimes referred to as "warm clouds". Likewise, clouds that are colder than freezing are sometimes referred to as "cold clouds." Cold clouds may have cloud bases that are warmer than freezing. Precipitation can occur naturally from both types of clouds.

In warm clouds, cloud droplets that survive long enough and especially when cloud drops are of different sizes, may result in cloud water droplets colliding and growing such that they may reach raindrop sizes that can fall to the ground as rain. This process is known as "collision/coalescence." This process is especially important in tropical clouds but can also occur in more temperate climates.

In cold regions (< 0^0 C) of clouds, cloud water droplets may not freeze. The reason for this is the purity of the cloud water droplets. In a laboratory environment, pure water droplets can remain unfrozen down to a temperature of -39^0 C. Natural impurities in the atmosphere can cause cloud droplets that are colder than freezing (usually referred to as being supercooled) to freeze. These supercooled cloud droplets are what causes icing to occur on aircraft. The natural impurities often consist of tiny soil particles or bacteria. These impurities are referred as "freezing nuclei." A supercooled cloud droplet can be frozen when it collides with one of these natural freezing nuclei thus forming an ice crystal. This process is known as "contact nucleation." A water droplet may also be formed on a freezing nucleus, which has hygroscopic (water attracting) characteristics. This same nucleus can then cause the water droplet to freeze at temperatures less than about -5^0 C forming an ice crystal. This process is known as "condensation/freezing." Once an ice crystal is formed within a cloud it will grow as cloud droplets around it evaporate and add their mass to the ice crystal eventually forming a snowflake (diffusional growth). Ice crystals can also gain mass as they fall and contact then freeze other supercooled cloud droplets, a process known as "riming." These snowflakes may fall to ground as snow if temperatures at the surface are approximately 0^0 C or colder. They may reach the surface as raindrops if surface temperatures are warmer than freezing.

Research conducted in the late 1940's demonstrated that tiny particles of silver iodide could mimic Mother Nature and serve as freezing nuclei at temperatures colder than about -5^0 C. In fact, these silver iodide particles were shown to be much more active at temperatures of ~ -5^0 to -15^0 C than the natural freezing nuclei found in the atmosphere. As a consequence most of man's modern day attempts to modify clouds to produce more precipitation (or reduce hail) have used silver iodide as a seeding agent. By definition, these programs are conducted to affect colder portions of clouds; typically cloud regions -5^0 C or colder (e.g., "cold clouds"). These programs are sometimes called cold cloud or glaciogenic seeding programs.

There has been some research and operational programs designed to increase precipitation from "warm clouds." The seeding agents used in these programs are hygroscopic (water attracting) particles typically some kind of salt (e.g., calcium chloride). These salt particles can form additional cloud droplets, which may add to the rainfall reaching the ground. This seeding technique, sometimes referred to as warm cloud or hygroscopic seeding, can also modify the warm portion of clouds that then grow to reach temperatures colder than freezing. Research programs conducted in Australia, Mexico, and South Africa targeting these types of clouds indicated that such seeding did increase the amount of rainfall from the seeded clouds.

TROPICAL CLOUD SEEDING PROGRAMS

Cloud seeding programs have been and continue to be conducted in tropical environments. Early research programs were conducted in the 1960's and 1970's in the Caribbean and in Florida. The Florida Area Cumulus Experiment (FACE), a research program, was conducted over southern Florida in two phases from 1970-1976 (FACE 1) and 1978-1980 (FACE 2). Seeding was conducted by aircraft dropping ejectable silver iodide impregnated flares into growing towering cumulus clouds as they reached the -10^0 C height. Randomization was used such that approximately 50% of the qualifying clouds were seeded. The remainder were left unseeded. Weather radars were used to estimate the amount of rainfall from seeded and non-seeded clouds for six-hour periods following selection of cloud candidates. The mean of the estimated seeded rainfall was divided by the mean of the estimated not-seeded rainfall yielding a ratio such that a ratio over 1.0 would indicate more rainfall fell from seeded clouds. The seed/no seed ratio for FACE 1 for the total target area was 1.23 indicating 23 % more rainfall over the target area (Woodley and Barnston, 1982). This result was statistically significant at the 0.09 level. FACE 2 was designed in an attempt to replicate the indicated positive results achieved from FACE 1. FACE 2 was terminated prematurely and the calculated number of samples to achieve statistical significance was not obtained. In addition, there was one very large not seeded event that tended to dominate the statistics. When this one outlier was removed, the indicated total target seeding effect was 1.28 (an indicated 28% increase) with a significance level of 0.13 (Woodley and Barnston, 1983).

CLOUD SEEDING TECHNIQUES USED IN SEEDING CUMULUS CLOUDS

Cumulus clouds are the most common type of cloud that occur in tropical regions. A common evolution in cumulus clouds is a progression from cumulus congestus to towering cumulus to cumulonimbus (thunderstorm). A significant amount of rainfall in tropical clouds is derived from thunderstorms. As previously mentioned, seeding clouds with silver iodide is directed at seeding regions of naturally occurring clouds that are colder than approximately -5^0 C that contain supercooled water droplets. Numerous previous studies have shown that the tops of growing towering cumulus clouds in the tropics frequently rise to the -5^0 C level or colder. The pioneering work conducted by the U.S. Environmental Science Services Administration (ESSA) and the National Oceanic and Atmospheric Administration in the Caribbean, Atlantic Ocean and Florida (FACE 1 and FACE 2) targeted growing cumulus clouds whose tops were passing through the -10^0 C level. Such clouds were found to contain significant quantities of supercooled liquid water. Figure 2 provides an example of a towering cumulus cloud, and Figure 3 provides a photograph of an aircraft equipped with an ejectable silver iodide flare rack. The typical approach used in FACE and subsequently in other summer research and operational seeding programs was to have the seeding aircraft fly at the –5 to -10^0 C level during periods that the development of towering cumulus clouds is expected. The seeding aircraft then penetrates the tops of developing towering cumulus clouds when they reach the height of the aircraft flight level. If vertical updrafts and supercooled liquid water droplets are encountered, from one to several flares are fired from the aircraft. These flares are ignited as they are ejected from the aircraft. The combustion process creates literally trillions of tiny particles of silver iodide that are ingested by the cloud as the flare falls through the cloud updraft (a region with high concentrations of supercooled water droplets). The flare, depending upon its size, falls approximately 610 to 1830 meters before being completely consumed by the combustion process. The silver iodide particles interact with the cloud microphysics to form tiny ice crystals that can subsequently grow into snowflakes that fall towards the earth, melting as they pass through the freezing level and reaching the ground as raindrops thus augmenting the natural rainfall. The suggested effects of seeding cumulus clouds in this manner are increases in cloud top heights and increases in the duration of the clouds. Such effects are frequently attributed to a “dynamic” seeding effect theorized to be caused by the release of the latent heat of fusion due to the freezing of the supercooled cloud droplets. This release of heat can increase the cloud updrafts which can lead to an increase in cloud tops and possibly the duration of the cloud.. Subsequently, downdrafts from near the base of seeded clouds may be enhanced causing convergence zones to develop in the lower atmosphere around the seeded clouds. These convergence areas can lead to the development of other cumulus clouds which may also grow into thunderstorms which in turn produce more rainfall than would have occurred naturally even though these subsequent clouds were not directly seeded.

OPERATIONAL TROPICAL CUMULUS PROGRAMS CONDUCTED BY NAWC

North American Weather Consultants (NAWC) has conducted a number of operational cloud seeding programs in tropical environments. Operational programs are conducted with the goal of realizing a direct benefit from the seeding activities. Research programs are conducted to gain a better understanding of how cloud seeding works and to demonstrate seeding effectiveness.

NAWC has applied the seeding techniques utilized in the earlier ESSA and NOAA research programs. This technique is based upon aircraft penetrations of growing towering cumulus clouds at the –5 to -10^0 C level and ejection of silver iodide impregnated flares into the tops of these clouds. One of these programs was conducted for a five-month period over the Hermitage and Mona Reservoir watersheds in Jamaica during the summer of 1975. These reservoirs are the primary source of culinary water for Kingston. This program was organized to attempt to partially alleviate the very low water levels in these reservoirs experienced in April. The Jamaica Water Commission funded the program. Relatively few seeding opportunities occurred during the months of April and September. Forty seeding flights were conducted during the four-month period of May – August. An evaluation of this seeding program was performed by the Meteorological Service of Jamaica. This evaluation was based upon an historical target/control evaluation approach. The results of this evaluation suggested a 26% increase in target precipitation during the four-month period. The Meteorological Service of Jamaica also estimated the increases in streamflow into the two target reservoirs, Hermitage and Mona. The resulting increases were 125 and 40 million gallons respectively. A comparison of the costs of the program versus these inflow amounts indicated a cost of $0.37 cents per 1000 gallons of inflow (Griffith and Brown, 1976).

Figure 2 Towering Cumulus Cloud

Figure 3 Belly-Mounted Ejectable Flare Rack

NAWC conducted programs in the San Angelo, Texas area during the summers of 1985, 1986, 1987, and 1988. These programs were designed to enhance runoff into two reservoirs located west of San Angelo, which provide culinary water to the city. An evaluation of the 1985 and 1986 programs suggested an increase in target precipitation of +26% (Griffith, 1987).

NAWC also conducted cloud seeding programs for the Chixoy Reservoir drainage in Guatemala (1992, 1994) and the El Cajon Reservoir drainage in Honduras (1993, 1994, 1995, 1997). These programs were sponsored by Empressa Electrica and Instituto Nacional de Electrification in Guatemala and the Empressa Nacional de Energia Elecvtrica in Honduras. Both programs had as a goal increasing runoff into the respective reservoirs, which in turn would be used to increase hydropower production. Both programs were initially begun due to drought conditions that had lead to low reservoir levels, which had resulted in rather dramatic reductions in hydropower production. An evaluation of the 1992 program in Guatemala indicated an increase in precipitation in the target area of 17 percent. Evaluations of the 1993, 1994 and 1995 programs in Honduras indicated increases in precipitation of 9 to 15 percent. Certain assumptions were made to estimate the amount of runoff produced during the 1995 program. This estimate amounted to 366,876,000 m^3. Calculations of the cost of the 1995 program versus the value of this additional inflow were made using certain assumptions. The resultant benefit/cost ratio was estimated to be 23.5/1.

FEASIBILITY/DESIGN STUDIES

“Planning has been defined as the orderly consideration of a program from the original statement of purpose through the evaluation of alternatives, to the final decision on a course of action. There is no predefined process that always leads to the "best" decision, because each cloud seeding program is unique in its physical and financial setting. There is no substitute for sound professional judgment by well-qualified, experienced individuals in program planning, design, and management. Each individual step toward a final program design should be supported whenever possible by quality quantitative analyses rather than estimates.” ASCE, 2006.

The term "feasibility study" refers to the examination of the local climate and cloud characteristics, to determine whether or not cloud seeding technology has a reasonable expectation of increasing precipitation. The term "program assessment" refers to the evaluation of the program itself when it is actually conducted. The program assessment may include operational decision-making procedures, forecasting, and most often, the effects of the program on precipitation.

The feasibility of a program depends largely upon two factors. First, is there a scientific basis for the work proposed that could yield the desired additional precipitation? Secondly, even if such a basis exists, is the cost of implementing a program based on the known science affordable? The latter depends heavily upon the combination of available financial resources and the expected return in additional water, in other words, the benefit/cost ratio. When possible, the feasibility study for a program should draw significantly from previous research and well-conducted operational programs that are similar in nature to the proposed program (e.g., similar topography, similar precipitation occurrences, etc.). There are logistical/practical considerations as well. For example are there adequate airport facilities at which project-seeding aircraft can be based? Are there alternate airfields within range in case the primary airport visibility drops below minimum operating conditions due to weather? Does a majority of the suitable cloud developments occur during day light hours during which airborne seeding is practical? Are there any existing weather radar installations that cover the area(s) of interest?

The American Society of Civil Engineers (ASCE) in their "Standard Practice for the Design and Operation of Precipitation Enhancement Projects" recommends the performance of a customized project design prior to implementation of a cloud seeding program (ASCE, 2004). As outlined in this ASCE publication, a comprehensive feasibility/design study would address a number of issues including: 1) project scope, 2) targeting and delivery methods, 3) seeding agent selection, 4) meteorological data collection and instrumentation, 5) selection and siting of equipment, 6) legal issues and 7) environmental concerns. Other issues that would be included would be: estimates of the frequency of seedable events, estimates of the potential magnitude of seeding increases, development of suspension criteria to avoid seeding during potential flood producing events, and estimated costs to implement and conduct a program.

SUMMARY

Cloud seeding may be an effective tool used in augmenting water supplies in the Caribbean. The potential for augmentation probably lies within the range of 5-15% increases in precipitation although some project evaluations have indicated results exceeding 20%. Cloud seeding programs can typically be organized rather quickly without the need for any long-term commitments or major infrastructure costs. The cost of augmented water will undoubtedly be much less than other potential augmentation options like desalinization. The performance of a feasibility/design study is recommended prior to the consideration of the implementation of a cloud seeding program.

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