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CLOUD SEEDING IN CHILE

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ABSTRACT. The historic background and a current cloud seeding operations project in Chile are discussed. The present affected areas are located in northern and north-central Chile, which are very productive agricultural areas with extremes in annual precipitation totals. Recent cloud seeding efforts were initiated in November 1979 using airborne silver iodide pyrotechnics. The discussion on this recent effort covers the first two year period through October 1981. This mission oriented program is not designed as a scientific experiment. However, some possible results are discussed.

1. HISTORY OF CLOUD SEEDING IN CHILE

Chile is more than 2,600 miles long, yet its average width is less than 130 miles. Located between the Andes on the east and the Pacific Ocean on the west, it has a wide variety of climates. In the north are some of the driest areas in the world and at some locations in the south rainfall is recorded almost every day. This extreme variety of cloud conditions suggests abundant opportunities for weather resources management programs.

Within the country are excellent conditions for a number of agricultural crops. This is especially true of a wide variety of fruit, whose economical significance is enhanced by the fact that the seasons are reversed in relation to Chile's most important foreign markets in the northern hemisphere. The recent opening of the Chilean economy to the world markets has increased the demand for Chilean agricultural products. This encourages Chilean farmers to produce more and better crops through the use of improved and modern intensive production techniques. The situation has also increased the amount of land under production for export fruits in the areas with the best soils and climates. However, the current amount of land which can be irrigated (about 1,200,000 hectares) is limited. The main problem now for the development of new irrigated lands is the limited supply of irrigation water, especially in the areas best suited for export crops.

Most of the rain in Chile occurs in the winter (April-September) when very little irrigation water is required. Farmers in many watershed areas are pressing for the construction of regulation dams which would enable them to accumulate water for use during the growing season. These dams must be large enough to store water during excessively rainy periods in order to fulfill the requirements during dry years, inasmuch as the annual rainfall amounts are extremely irregular. The situation appears to be worsening each year, with a noticeable tendency toward a decrease in the average annual rainfall and an increase in the frequency of extremely dry years.

Consideration must also be given to the growing competition for water coming from the increasing urban, industrial and mining developments. The arguments in favor of these activities suggest that they are more profitable socially and/or economically than agriculture. This diminishes the supply of water for farming and is another factor in forcing the farm community to adopt more efficient irrigation techniques.

An additional factor worth mentioning is the Agrarian Reform which took place between 1964 and 1973. During this period most of the productive farms were expropriated. After 1973, when these farms were divided and finally assigned to new farmers, there was a dramatic change in both the soil culture systems and the soil rotation practices. The smaller size of the new farms made it necessary to have the soil in production each year in order to produce enough for survival. This produced a sudden increase in the demand for irrigation water.

The lack of water due to the above causes discourages investments by reducing security. However, the foreign demand and high prices are strong reasons why the Chilean Government and the investors have considered cloud seeding as a possible economical and reasonable alternative for increasing the water supply and providing an additional security of investments.

It is curious to note that, unlike many groups in the western United States, the hydroelectric power company in Chile has not indicated any significant interest in enhancing their water supply by cloud seeding techniques. Like other areas of the world, a small increase in water supply would be extremely profitable during the current years when the demand for power is growing and there is a substantial annual increase in the cost of any alternative source.

Cloud seeding programs designed to increase precipitation is not a new subject in Chile. Interest in rain enhancement has frequently emerged, especially when Chile enters a dry weather cycle. The problem is similar to one found in other areas of the world. By the time the cloud seeding activities are finally initiated, the crop disaster is extreme and the cloud conditions are such that minimal opportunities are present and results are perceived to be questionable. As a result, the subject lies fallow until the next drought period. Fortunately, this perception is disappearing and Chile has been working continuously with cloud seeding efforts since 1976.

The past efforts to artificially stimulate precipitation in Chile have been numerous. The earliest references go back to 1948 when President Gabriel Gonzales Videla ordered the Chilean Air Force to attempt the stimulation of cumulus clouds with dry ice over the Province of Coquimbo (now Region IV). Some 40 flights were accomplished using World War II Mitchell B-25 bombers. During 15 of these flights, clouds suitable for treatment were located. Based on cloud observations, the flight crews estimated that some precipitation was produced only during three seeding events. As part of these experiments, the Universidad Tecnica Federico Santa Maria also conducted some field experiments using silver iodide in cooperation with the Chilean Air Force. During these early field experiments and operations trials, some isolated efforts at rainfall augmentation were conducted by farmers in the watersheds of the Huasco, Elqui and Limari Rivers. In these cases, silver iodide ground generators of unsophisticated design were utilized. Results were uncertain. During the drought of 1958, the Cooperativa de Agricultores del Valle de Elqui organized a cloud seeding operation to begin during the 1959 rain season. The program was terminated because 1959 produced abundant rainfall. Interest deteriorated until the next drought period.

In 1962, Dr. E. G. Bowen, an Australian scientist working for the Commonwealth Scientific and Industrial Research Organization (C.S.I.R.O.) in Australia, produced a report for the Chilean Government on the feasibility of using weather modification to increase the water supply in Chile. Based on that report, Mr. Jose Cristoffanini T. of the "Consejo Superior de Fometeo Agropecuario" under request from the Minister of Agriculture, prepared a proposal to initiate a program of Experimental Modification of the Weather. Between the years 1967 and 1971, a severe drought persisted in Chile. The proposal by Mr. Cristoffanini produced an active program called "Proyecto M.E.T.A." (Modificacion Experimental del Tiempo Atmosferico). This project, sponsored by the Universidad del Norte, the Chilean Air Force, and the Ministry of Agriculture, was conducted near Arica in the extreme northern portion of Chile. During 1968, flights were also conducted on an emergency basis over Santiago. Results were uncertain. The M.E.T.A. Project continued until 1971. During the active periods, a number of difficulties were noted with aircraft operations; obsolete aircraft, lack of availability, maintenance problems, and pilot rotation. During one of the cloud seeding flights an AT-6 aircraft crashed and the pilot was killed.

The M.E.T.A. Project received technical support from the Australian Government, which also donated the cloud seeding equipment. Dr. E. E. Adderley came to Chile as a Technical Advisor during this period. No final report was written on this program. However, in 1970 Dr. Adderley produced a report on cloud seeding operations of the two previous years. In this report, he stated that the expectation from seeding was a 40% increase in precipitation, according to the information gathered during those two years. Although there was a strong inference that a large difference existed between precipitation on seeded and non-seeded days, the sample was small. Dr. Adderley recommended that seeding should be continued. In August 1968, the power company in Chile elected to carry on a test program near Santiago, using four silver iodide ground generators positioned in various locations throughout the mountains surrounding the city. There is no summary report or evaluation available for this program.

In 1976 Chile suffered another severe drought. In September of that year, Mr. Guillermo Duarte T., a meteorologist and TV Weather Man, offered his help to the Chilean Farmer's Association, in initiating a weather modification program. The President of the Association, later to become Minister of Agriculture in Chile, enthusiastically supported the program and agreed to finance a few test cases. After three apparently successful trials, the program was transferred to the Ministry of Agriculture where it was placed under the Servicio Agricola y Ganadero (S.A.G.). Although many operational aspects have changed, weather modification in Chile continues as a part of S.A.G.

The weather modification system of Mr. Duarte was based on the use of a water solution of hygroscopic salts (NaCl and urea). It was believed that the use of a solution would produce a much easier dispensing system. However, the use of large airplanes was required to carry enough seeding material. Prior to Mr. Duarte's early death in 1979, some 50 seeding flights were conduced around Santiago, Copiapo, Vallenar, LaSerena, Ovalle and six flights were conducted near Punta Arenas in the far south of Chile. A variety of aircraft types were used such as the Twin Otter, Piper Apache and a Fairchild F-27. During the seeding activities accomplished over Punta Arenas, a flare gun and pyrotechnics were provided by Dr. Pierre St.-Amand from China Lake, California.

In 1979, there was no rain recorded in Santiago until June 22nd, making it the driest year in history. On that day, a layer of stratus about 800 meters thick was noted over the Santiago area and no rain was expected. Local smog and drought conditions were so severe that a cloud seeding flight was conducted under request of the local government. About 1.5 hours after seeding was initiated some 80 km west of Santiago, a drizzle began to fall over the city. Total precipitation from this drizzle was less than 1mm, but it did clear the smog and renewed public perception for a better year. Fortunately, rain continued in the weeks that followed and 1979 produced a slightly above normal total.

From a scientific point of view, results from these early experimental seeding efforts have been inconclusive. Like programs in many areas of the world, these seeding trials were designed as an operations emergency endeavor. All clouds were treated whenever they appeared suitable. No statistical work has been conducted. However, observations by aircraft crews and ground personnel have strongly suggested that positive effects were produced simply because rains occurred in the seeded areas and not in the unseeded locations.

After Mr. Duarte's death, it has been difficult to continue with hygroscopic seeding. The original concept for this program was to base the

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the operations in LaSerena, near to the selected area of effect. Using the Fairchild F-27 as the cloud seeding aircraft, the cost was prohibitive. A decision was then made to study the possibility of using silver iodide as a seeding agent, inasmuch as this would allow the use of a much smaller aircraft at lower operations cost, and still position the aircraft near to the chosen area of effect.

Atmospherics Incorporated was invited to visit Chile, investigate the feasibility of silver iodide seeding, and prepare a report covering the various aspects of a possible operations program. Mr. Thomas Henderson visited Chile and conducted this investigation. The study and report were concluded in August 1979. The findings supported those of Bowen and Adderley, in which there was a strong recommendation to change from the use of hygroscopic materials to artificial ice nuclei systems. This change was made in October 1979, when the Chilean Government acquired an Enterprise Electronics radar system and formulated an agreement with Atmospherics Incorporated to initiate a cloud seeding program over various areas of northern Chile. The control of this program has remained within the Servicio Agricola y Ganadero.

2. OBJECTIVE

The exclusive objective of the current cloud seeding program is to enhance precipitation over the watersheds to the east of some arid and semiarid agricultural areas. The largest precipitation amounts occur over the high Andes, and cloud conditions are most suitable for treatment over this high terrain. Inasmuch as there are very few artificial reservoirs along the rivers in the operational areas, the program is focused on increasing the snowpack in the high Andes which release water at a slower rate throughout the year. Westerly from these high elevation areas, occasional cloud formations develop which are suitable for treatment. These are seeded to produce additional rainfall directly into the tributary streams and their relevant watersheds.

3. SELECTED AREAS

3.1 Summer months

During the summer season of 1979/80 (November 1979 through February 1980), the project was operated from Vallenar. This is the same operations area as used during the winter months. However, during the summer of 1980/81 (November 1980 through February 1981), the project was operated from the Buitre airfield near Arica. This operations area is shown in the upper portion of Figure 1.

There are several individual watersheds within this summer season operations area. All but one are normally dry washes. From north to south these watersheds include the Lluta, San Jose, La Higurea, Vitor, Camerones and the Tilliviche.

3.2 Winter months

The winter season operations area (March through September) consists of four distinct contiguous river basins. These are shown in the lower portion of Figure 1. From north to south these

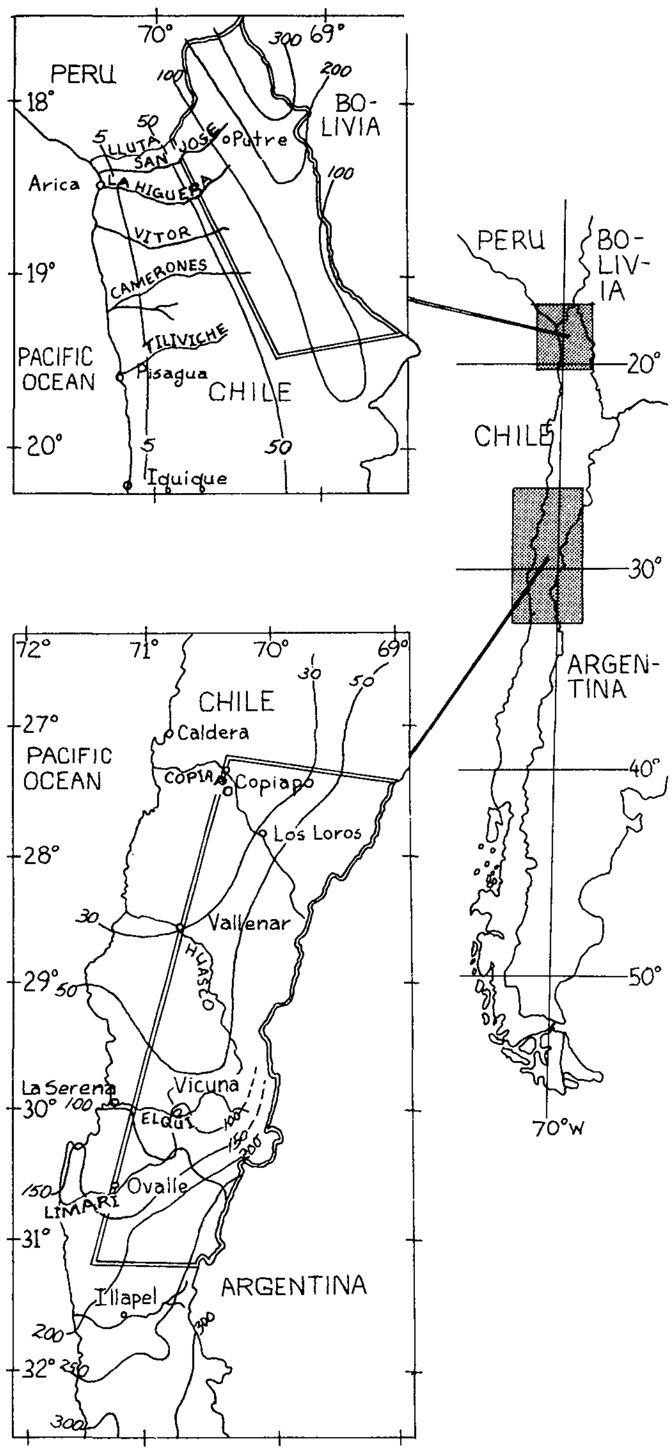

Figure 1. Operational areas. Summer months (upper), winter months (lower).

waterheds include the Limari, Elqui, Huasco, and the Copiapo Rivers.

The reasons for the selection of this particular area for winter seeding operations are straightforward. South of this area, there is a substantial increase in natural precipitation. North of the area there are virtually no wintertime storm systems, since all of the mid-latitude wave cyclones are effectively blocked by the sub-tropical anti-cyclone. The northern operations area is considered to be the southern boundary of the Atacama Desert, where the meager precipitation might be augmented for the benefit of all inhabitants within the area.

4. GENERAL METEOROLOGY

Summertime precipitation is primarily produced by the action of a thermal low which forms over South America, achieving its greatest development during the warmest months of the year. This thermal low may produce convective clouds as high as 10,000 meters MSL. Ths summer cloudiness forms first over Argentina and Bolivia, later migrating to Chile or forming directly over the area. For this reason, the phenomenon has been given the name "Bolivian Winter" in north Chile. Thus, the summertime precipitation is associated with the meteorology of the continent where the important moisture source for cloudiness is the Atlantic Ocean.

Winter precipitation in Chile is produced primarily by the action of mid-latitude wave cyclones which move in from the Pacific and cross Chile from west to east. These cyclones normally produce persistent orographic cloudiness as the moist Pacific air flows up and over the Andes.

5. EQUIPMENT

5.1 Meteorological radar system

An Enterprise Electronics weather radar system (WR100-2) provides information on precipitation characteristics within the operational areas. This 5.4 cm radar operates on a frequency of approximately 5,600 MHz. The system has a pulse duration of two micro-seconds and a pulse repetition frequency of 256 cycles. The parabolic antenna provides a 2^o pencil beam and rotates through 360^o azimuth throughout an elevation range from -1^o through $+60^o$. Normal operations are conducted at an elevation angle of 4.5^o due to the various terrain features west of the Andes.

The radar system is installed in a Winnebago motorized unit which contains an auxiliary electric power unit, making the entire system completely self-contained and mobile. Four screw jacks provide leveling and stablization while the radar is operated in any given location. Routine monthly checks of the power output and receiver sensitivity ensure the consistent performance of the various components.

5.2 Cloud seeding aircraft

A turbocharged Piper Aztec "F" aircraft is used for the delivery of silver iodide seeding material. A Robertson STOL kit provides the aircraft with operational capabilities from relatively short runways. The Aztec is equipped with dual VOR, ADF, and communications systems. An additional FM radio is installed for communications between the aircraft and radar. The aircraft is also equipped with a weather radar system and an HF communication radio.

All seeding operations have been conducted with pyrotechnic generated silver iodide smoke particles. The aircraft is equipped with both wing racks for the use of end-burning pyrotechnics and multiple position racks for ejectable pyrotechnic units.

6. GENERAL OPERATIONS

The general criteria established for seedability has been the appearance of radar echoes stronger than 12 dBz within or near the target area that have, or are expected to have, supercooled cloud tops. When such echoes are observed, the seeding aircraft is dispatched to the appropriate area and seeding commences.

While the aircraft is in radar and radio contact, the seeding is controlled by the radar meteorologist at the radar site. However, when the aircraft is more than about 80 nautical miles distance from the radar station, both radio and radar contact are often lost due to line-of-site limitations in the mountain areas. In those cases, the seeding decisions are made by the pilot in command of the aircraft.

Three types of silver iodide pyrotechnic devices are available for the actual seeding operations. These are 10 gram and 20 gram ejectable flares used for cloud top or cloud penetration seeding, and the 20 gram end-burning units for cloud base seeding. During seeding operations the aircraft is flown at a speed of approximately two nautical miles per minute. The 20-gram end-burning pyrotechnics are each consumed in about 8 minutes so the linear concentration of silver iodide is about 1.25 grams per nautical mile. When the aircraft is flown at a flight level of -10^oC, and assuming there are about 10^{14} nuclei per gram of silver iodide effective at that temperature, this would correspond to about 6.75×10^{10} nuclei per meter along the seeded path.

When it is not possible to fly at an altitude of about -10^oC, cloud base seeding is accomplished in the updraft areas with the 20-gram units, or seeding is accomplished at cloud top with the ejectable pyrotechnics. Aircraft seeding flights last from two to four hours and are usually conducted in mid or late afternoon.

Safety considerations limit some of the cloud treatment alternatives. Throughout the target areas there is a lack of precise navigation aids for IFR flights. Wandering off course under either VFR or IFR conditions could mean crossing international borders and this is avoided with considerable persistence. Wintertime cloud bases are often less than 1,000 ft. msl, with tops ranging up to 20,000 ft. msl in multiple layers. The only airways lie along the coast. Flying IFR off airways can be hazardous because terrain elevations are above 20,000 ft. msl in some areas along the borders with Argentina and Bolivia.

Navigating under IFR conditions off airways is difficult but not impossible. There are VOR stations at Santiago and Antofagasta, but the great distances limit there usefulness. Several radio stations and radio beacons are operational throughout the areas, but over the Andes Mountains they are often weak, intermittent, and sometimes unreliable. An IFF transponder system installed in the ground based weather radar system provides considerable assistance with flight course guidance, but it cannot give terrain clearance information to the pilot.

Seeding is often suspended in the face of impending severe weather to avoid contributing to, or appearing to contribute to, a possible flood situation. Such a situation occurred on 11 April 1980 when, after five straight days of seeding and rain, a flood threat was noted and seeding was suspended for 10 days. No significant damage occurred during this time period. In late July 1980, the snowpack in the Vallenar and Copiapo watersheds was so extensive that some concern was expressed about flooding during spring runoff. Consequently, seeding was suspended in these watersheds for the period August to September 1980. Subsequently the spring runoff was well above normal but no major flooding occurred.

7. CLOUD SEEDING ACTIVITIES

During the 1979/80 summer season, the aircraft was operated from the Vallenar Airport. The radar was installed on a small hill some 10 km west of the airport at a place called Buena Esperanze. Radar surveillance was maintained each day and cloud seeding was accomplished on those days when suitable convective conditions developed over the high Andes.

During both of the March-September winter seeding activities in 1980 and 1981, the radar and aircraft were based at the La Florida airport near La Serena. Seeding occurred each time a mid-latitude wave cyclone moved across Chile from the west. Most of the wintertime seeding has been accomplished in the moist west-northwesterly flow ahead of an approaching cold front from the Pacific. After frontal passages the subsidence inversion rapidly strenghtens and lowers, which soon limits any post-frontal convection. Wintertime seeding has been accomplished under orographic cloud conditions and embedded convective cells. Orographic clouds may persist for several hours following a frontal passage.

During the November-February summer seeding period of 1980/81, the radar and aircraft were operated from the El Buitre airfield near Arica. Again, radar surveillance was maintained each day and seeding flights were dispatched on those days when appropriate cloud conditions developed over the high Andes.

A summary of seeding activities conducted during each of the four seasons is shown in Table 1.

8. CONCLUDING REMARKS

This cloud seeding project has been designed as an operational program and no provisions have been made for a detailed scientific evaluation of results. A number of other problems provide further complications to significant evaluations. These are (1) operational areas have not been consistent, (2) there is a scarcity of long-term meteorological data, and (3) the project has been operated for a short time period.

TABLE 1.

CLOUD SEEDING OPERATIONS SUMMARY

Period	Seeding Flights (number)	Flight Time (hours)	Total Pyros (number)	Total AgI (grams)
Nov'79 - Feb'80	29	66.8	100	2000
Mar'80 - Sep'80	24	62.5	124	2480
Nov'80 - Feb'81	33	97.0	173	3460
Mar'81 - Sep'81	13	30.9	69	1380
TOTAL	99	257.2	466	9320

Streamflow runoff values have been suggested as a possible indicator of results. However, varying irrigation practices from year to year, plus difficulties with surface water measurements, make it difficult to use streamflow data. There are some "natural flow" data available which might be used with some caution.

Long term precipitation stations are minimal within the operational areas, particularly at the higher elevations. Some of the longer term precipitation stations are within the operational areas at El Transito and Conay. At Conay the precipitation amount of 238.3 mm in 1980 is the highest ever recorded in the 15 years of record. At El Transito the precipitation amount of 177.13 mm in 1980 has only been surpassed once during the 40 years of record. By themselves these figures certainly do not form a statistical proof, but taken together with persistent streamflow in "dry wash" areas, they do provide a <u>suggestion</u> of some positive result.

An estimated increase of 10% in the water reserves through a continuous cloud seeding program would encourage agricultural investments and produce immense benefits for the agricultural and economic development of the region.

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