# Artificial rainfall enhancement program in Cuba by convective cloud seeding. Acheivements and shortcomings in the period 2005-2010.


Daniel Martínez, Carlos A. Pérez, Guillermo Puente, Félix Gamboa, Sadiel Novo, Ibis Rivero, Graciela Angulo, Ismael Pomares, Alexei Gamboa , Elsa Velazco , Michel Rodríguez, Ernesto Chang
Institute of Meteorology, La Habana, Cuba. C.P. 11700
Tel-Fax: 537-881-3411 e-mail: daniel.martinez@insmet.cu

Victor Petrov, Boris Koloskov,
Agency of Atmospheric Technologies (Agency ATTECH, ROSHYDROMET)
Novovagankovsky per. 8, Moscow, 123242, Russia.
Tel: +7(495)255-2372; Fax: +7(495)255-2134; e-mail: attech@mail.ru

Zhanyu Yao
Chinese Meteorological Administration. Baijing. yaozy@cams.cma.gov.cn.


## 1. Introduction

To mitigate the effect of a severe drought which affected the Eastern part of Cuba in 2004 and the beginning of 2005, the Cuban Government decided to support the development of an operational and research Rainfall Enhancement Program. This Program was composed by a research project, designed to continue and complement the previous research program, developed in the 80s-90s and an operational cloud seeding project to enhance precipitation in the areas most affected by drought.

## 2. EXPAREX

The research project of this Program was the Randomized Convective Cold Cloud Seeding Experiment in Extended Areas (EXPerimento aleatorizado de siembra de nubes en AReas EXtensas, EXPAREX), based in silver iodide seeding from the tops of growing convective clouds, which design, general description and physical foundations were presented in Martínez et al. (2007) and Pérez et al., (2008). This experiment is being implemented in Camagüey and the adjacent provinces of Ciego de Ávila and Las Tunas from August 2005 as the continuation and complementation of the previous results of PCMAT (Koloskov et al., 1996).

The experimental units were defined as the group of clouds located within a circle having a radius of 25 km and centered at the location of the initial treatment. The target clouds within the experimental unit were growing convective clouds having, at least 0.5 g/m3 of supercooled cloud water (SCW), updraft velocity greater than 5 m/s and top temperature of -7 to -20oC, as described in detail in Martínez et al. (2007). The clouds were seeded from an instrumented An-26 aircraft, under the dynamic seeding hypothesis. The glaciogenic reagent applied in the experiment is the pyrotechnic mixture of the Russian flares PV-26. This mixture has an output of $1.7 \times 10^{14}$ glaciogenic nuclei per gram at -10 $^{o}$C and $7.0 \times 10^{13}$ at -6 $^{o}$C. The flares burn during 40s and have a descending burning track of 1.5-2 km in moderate updraft.

The recommended flight level is near to the -7oC isotherm (5700-6000) m. Experimental units are selected jointly by the aircraft and ground team leaders, though the final decision corresponds to the aircraft. As soon as an experimental unit is selected, the envelope enclosing the randomized treatment decision is open by the seeding operator without any notice to any other member of the staff. The operator proceeds consequently for the rest of the clouds in the experimental unit, and the envelope is closed again after finishing working on it. In any case, the leading scientist gives the instructions to seed in the appropriate moment, but if randomized decision is “no seed”, he disconnects the launcher system and presses the buttons simulating seeding, so that the rest of the staff can’t notice the type of treatment actually applied. The experimental unit is being treated with subsequent penetrations of different cloud towers which are considered as apt for seeding.

For the control and track of cloud cells and precipitation, automated MRL-5 radar is used. The characteristics of the radar are the following: wavelength: 10.15 cm (S band); and peak power 510 kW; minimum detectable signal -136 dB/W; frequency; pulse duration 2.0 µs; beam width 1.5$^{o}$. With the radar and aircraft information, it is possible to follow the time evolution of cloud characteristics according to their development stage.

One of the main tasks of a floating target cloud seeding experiment is to determine the speed and direction of the target. The floating target tracking algorithm (Novo et al., 2007) is based on the hypothesis that the experimental unit will follow the average movement of the surrounding storms. At the treatment instant, which is taken as initial time for tracking, all present storms are identified. The circumference defining the experimental unit boundary is displayed, centered at the treatment point and extending to a radius of 25 km. In the next scan, every storm in the radar’s field of vision is tracked by choosing the new center positions that are located at the minimum distances from the centers in the previous scan, provided a certain limit distance is not attained. After all the storms have been identified in the new step, their displacement vectors are obtained. An average displacement vector of the storms contained inside a radius of up to 100 km neighborhood of the treated cloud is then calculated. This average displacement vector is assigned to the experimental unit. As output of the processing program, an image with the last maximum reflectivity map and the subsequent positions of the superimposed experimental unit circle is obtained, and also a text file including date, time, coordinates of the center and the main parameters of the seeding circle for every instant, as well as for the total tracking time. Rainfall rates "R" are estimated from radar reflectivity "Z" using a empirical standard Z-R relationship between these magnitudes, and is calibrated every day by the raingauge network of the area, (Gamboa el al., 2005).

An exploratory experiment was made from August 22 to October 10th, 2005, in which 21 experimental units were processed The randomization scheme was not applied in this season. However, the flight and seeding methodology of the EXPAREX experimental design were applied and the pilots and scientific crew were trained in locating and following the target in communication with the ground radar coordinator. In target clouds, SCW was measured to evaluate the ability of the flight leading scientist to choose appropriate clouds.

Figure 1 shows the frequency of occurrence of the mean and maximum values of SCW in the 2005 clouds. The analog distribution is shown for the clouds measured in the 1987-1990, during PCMAT. These are qualitatively similar, regarding the form of the distributions, but the mode, the mean and the maxima are, respectively of 0.4, 0.32 and 0.759 $gm^{-3}$ for 2005 and of 0.8, 0.5 and 1.03 $gm^{-3}$ for the period 87-90. The main reason for that decrease in SCW was the lower mean flight level temperature in 2005 (-10$^o$C), relative to 1987-1990 (-7,7$^o$C). Consequently, in the following experimental seasons the flight level was lowered from 6000 to 5700. The measured SCW distribution for 2006-2007 seasons are very near with PCMAT clouds, as shown in Fig. 2.

In 2006, the beginning of the experiment was delayed because of logistic reasons and it began as late as September 29, and continued until October 15. In 2007, the experiment extended from August 17 to October 4th. The following two years, the experiment could not be accomplished because of financial limitations, but it was continued in 2010, from September 1st to October 4th..

In the whole experimental period, 28 units were processed. Table 1 shows a list of the processed experimental units, including their lifetime T and the total rainfall volume Q produced by each of the units in kilotons, corrected using an adjustment coefficient obtained by comparison of the radar-estimated value with the raingauge network (Gamboa et al., 2005).

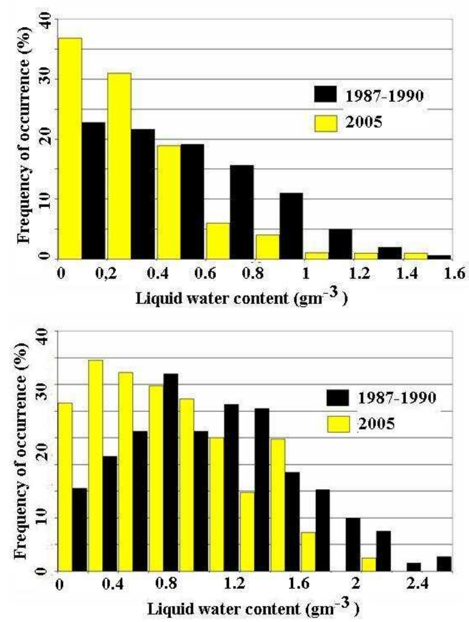


Fig. 1. Supercooled water content in EXPAREX clouds measured in 2005, as compared with PCMAT clouds.

Table 1. Date, time, lifetime and water volume of the processed experimental units.

| # | Initial date-time (lst) | T (min) | Q (kT) |
|---|---|---|---|
| 1 | 20061003-14:20 | 240 | 55273 |
| 2 | 20061006-15:20 | 400 | 12841 |
| 3 | 20061010-13:50 | 60 | 16 |
| 4 | 20061010-14:50 | 290 | 1141 |
| 5 | 20061011-14:50 | 350 | 1450 |
| 6 | 20061012-14:45 | 115 | 35 |
| 7 | 20061014-15:15 | 525 | 25391 |
| 8 | 20070824-14:05 | 550 | 9388 |
| 9 | 20070827-13:35 | 300 | 12133 |
| 10 | 20070830-14:00 | 275 | 5535 |
| 11 | 20070831-13:15 | 290 | 1453 |
| 12 | 20070910-14:05 | 540 | 4868 |
| 13 | 20070911-13:30 | 520 | 24378 |
| 14 | 20070915-13:40 | 705 | 6704 |
| 15 | 20070917-14:15 | 540 | 13014 |
| 16 | 20070918-14:30 | 615 | 4241 |
| 17 | 20070922-13:55 | 230 | 1029 |
| 18 | 20070927-13:15 | 655 | 14473 |
| 19 | 20070928-13:45 | 355 | 4975 |
| 20 | 20071004-13:25 | 595 | 11158 |
| 21 | 20100901-14:05 | 460 | 7363 |
| 22 | 20100905-15:00 | 240 | 7418 |
| 23 | 20100909-14:45 | 420 | 8949 |
| 24 | 20100911-14:40 | 350 | 8783 |
| 25 | 20100916-14:20 | 270 | 5972 |
| 26 | 20100921-13:15 | 260 | 1616 |
| 27 | 20100926-13:25 | 240 | 5475 |
| 28 | 20101002-13:55 | 710 | 1496 |

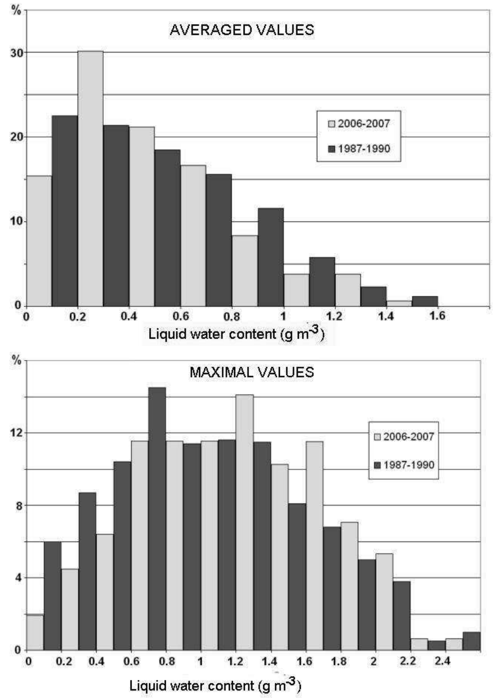


Fig. 2. Supercooled water content in EXPAREX clouds measured in 2006-2007, as compared with PCMAT clouds.

According to the experimental design, 120 experimental units have to be reached to evaluate the experiment. Therefore, the seeded/not seeded condition of each unit is still unknown.

### *3. Operational cloud seeding in the Eastern part of Cuba*

From 2005, an operational cloud seeding project was started in the province of Holguín, in the Eastern part of Cuba with the participation of advisers from the Chinese Meteorological Administration. In 2006 an An-26 aircraft was used for cloud seeding with Long B-2 Chinese flares, similar to the Russian PV-26 used in EXPAREX. The seeding methodology differed from the one used in EXPAREX in the fact that the clouds not always were penetrated, but sometimes were seeded from above the top, which allowed working on the side secondary towers of vigorous cloud systems. 154 convective clouds were seeded in about one month (July), most of them located in the western part of the Holguin province (fig. 3).

For a rough estimate of the rainfall increment, a non randomized historic regression method was applied. The Holguin province was selected as seeding area, and the Guantanamo province, which is located leeward of Holguín, was selected as control. The historic linear correlation coefficient of rainfall in July for both provinces was 0.73, significant at a 99% level. The estimated increment for July, 2006 was of nearly 30%.


Fig.3. Eastern part of Cuba, including the experimental and operational areas.

In subsequent years, the An-26 aircraft for this project was no more available, and it was replaced by a Yak-40, equipped with a launching system for PV-26 Russian flares. In 2007, 71 clouds were seeded in September, most of them in Holguín. In 2008, 82 clouds were seeded from June to September, and in 2009, 180 clouds were seeded from June to October.

From 2005 to 2006, a network of 23 silver iodide ground generators, manufactured by the Chilean enterprise HIDROMET, were installed in the Holguín province and some surrounding locations, near to mountainsides under the hypothesis that orographic lifting and thermal convection could serve as transport agents to carry the reagent up to the clouds. This network worked with stability till 2010. Subsequent numerical studies using a dispersion model showed that the concentration of reagent in the active regions of the clouds is not enough to produce seeding effect (González et al., 2009).

To estimate the effect of the integral operational program in Holguín, a historic regression approach was applied, using the seasonal rainfall totals for the western districts of the province as seeded area, and the eastern districts, located leeward of the seeding area, as control area. Fig. 4 shows the Holguin province, and the two areas. The district of Antilla (green in the map) was excluded from the regression for its peninsular character.


Fig. 4. Seeded (yellow) and control (white) areas for the estimation of seeding effect in Holguin for the period 2005-2010.

Rainfall totals were calculated for the quarter August-October of each year in the period 1964-1998.A linear correlation coefficient of 0.81 between the two sets of rainfall totals was found, with 95% significance level. Fig. 5 shows the scattering plot with the linear regression line. Dotted lines show the estimation errors of the variable 'y' (quarterly rainfall in the seeded area) as a function of the variable 'x' (quarterly rainfall in the control area).

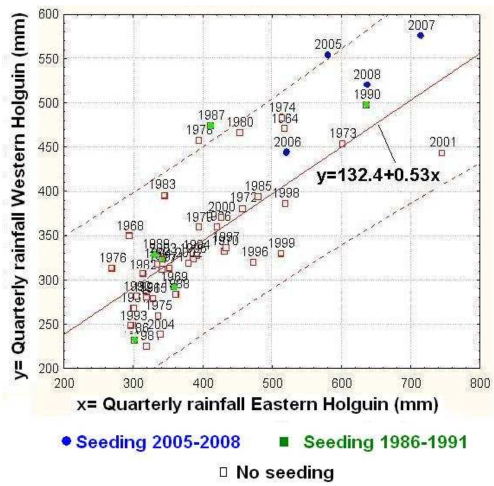


Fig 5. Historical regression line for quarterly rainfall in Eastern (control) and Western (seeded) Holguín for August-October.

In Fig. 5, the blue circles indicate the rainfall totals corresponding to the quarters from 2005 on, where operational seeded was accomplished, either from ground-based generators or from aircraft, or both. The green squares show the totals corresponding to the period 1986-1991, when massive cloud seeding was applied in Western Holguin. The empty squares indicate the years in which no cloud seeding was applied. As can be seen from the plot, in all the quarters of the recent cloud seeding period, rainfall in the seeded area exceeded the regression line forecast in 5%-10%, but is was not enough to exceed the error interval, except 2005, where it is practically on the error border line. This is valid also for the former seeding seasons in 1987-1990, except for 1986 and 1988, when quarterly rainfall was less than the regression forecast.

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