AN EXPLORATORY ANALYSIS OF THE POTENTIAL FOR RAINFALL ENHANCEMENT IN THE RANDOMIZED CONVEXTIVE COLD CLOUD SEEDING EXPERIMENT IN EXTENDED AREAS IN CUBA (EXPAREX)

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1. INTRODUCCIÓN

The Cuban Project for Artificial Weather Modification (PCMAT, in Spanish) began in 1979 in the Camaguey Meteorological Site (CMS) as part of scientific collaboration between Cuba and Russia. The earliest stage of the project included three major components: selection of appropriate site and period of the year to accomplish the experiment (1979-81); preliminary assessment of dynamical and microphysical characteristics of convective cold clouds in the site and an exploratory experiment (1982-1985).

The goal of this paper is to investigate the consistency of the behaviour of some properties of mixed phase convective clouds in CMS with the hypothesized precipitation enhancement as a response to dynamic seeding with silver iodide.

In the 1985 exploratory experiment, the hypothesis that the precipitation potential of clouds may be increased through dynamic seeding and a method for seeding convective clouds were both tested. This allowed us to draw some preliminary conclusions: the seeding of clouds with tops with height ranging from 6 to 8 km (-10 to -20 °C) leads to enhanced growth, as they last longer and exhibit a higher radar reflectivity. Suitable clouds must also have diameter between 2 to 5 km.

A confirmatory phase was designed for the period 1986 to 1990, including along with the seeding of individual convective clouds, clouds clusters extending over an area of 400-600 km². In conducting the confirmatory 1986-1990 experiment, a dynamical seeding conceptual model, which had been described and discussed by Wooddley and Sax (1976), was used. The treatment decision was randomized on a unit by unit basis and suitable convective cells were treated with AgI, in the case when the seed (S) decision was made, or were penetrated without being seeded in the case of no-seed (NS) decision. Neither the crews of instrumented aircraft nor of the service responsible for the monitoring of the seeding effect and the observation of experimental clouds, were informed about the results of randomization during the experiment.

In the confirmatory phase 46 individual convective clouds, 24 seeded and 22 not seeded and 82 clusters, 42 seeded and 40 not seeded, were studied. The analysis of radar data showed that the seeded clouds increases in lifetime, maximum height, area and rain volume by 120% for individual clouds and 65% for cloud clusters, as compared to unseeded ones, with a better than 5% level of significance.
On base of these encouraging results, a new phase was started in 1991, but in this case for extended areas with one or more cloud system. For this purpose, a floating experimental target with area of the order of 2000 km² was chosen as experimental unit. However in 1992 the experiment was interrupted due to funding problems.

At the beginning of 2005 the Cuban Government decided to support the resumption of the experiments in the CMS. As continuity of the PCMAT, a new experiment for the seeding of cold cumulus clouds in extended areas (EXPerimento aleatorizado de siembra de nubes en AReas EXtensas, EXPAREX), is being accomplished in CMS since 2005. The experiment was based on the revised dynamic–mode seeding conceptual model. Consequently, we have to answer the following question:

Do the dynamical and microphysical characteristics of cool cumulus clouds rising in CMS meet the criteria for the conceptual model?

The answer to this question is the main objective of this work.

2. FACILITIES

Two instrumented aircraft were used to collect the data, a twin engine IL-14 with ceiling of 3-3.5 km and cruising true airspeed of about 80 m s⁻¹, carried out measurement in the lower part of the clouds. For measurements in the upper part of clouds a twin engine AN-26 aircraft with maximum height of about 6 km and a cruising airspeed nearly 100 m s⁻¹ was used. IL-14 was equipped with a large particle spectrometer (LPS) and Nevzorov LWC probe IVO-1 (Nevzorov 1996), aircraft load complex for the measurement of velocities of vertical drafts, mean temperatures fluctuation (Dmitriev and Strunin, 1983). A similar instrument set was installed in the AN-26 aircraft excluding LPS, but including a photoelectric ice crystal counter Mee-120 (WMO, 1977) and a total water content (TWC) probe IVO-2 similar to IVO-1, but capable to measure both, droplets and ice crystals. Currently, in the EXPAREX field measurements we have been using an a similarly instrumented AN-26, but including in this occasion a LPS and excluding Mee-120.

For the control and track of cloud was used the dual MRL-5 radar. With the radar and aircraft information, it was possible to follow the time evolution of cloud characteristics according to theirs development stage.

3. DESIGN

After 15 years without field experiment and with a limited research activity, a new design was necessary to consider the development in physic of clouds and concepts related with dynamic seeding mode achieved in last years.

The design of EXPAREX experiment (Pérez et al. 2005) was aided by the results of the experiment in Cuba (1985-1990), West Texas 1987-1990, Thailand 1987-1990 and achievements of FACE-I and FACE-II as dynamic cloud seeding concept (Simpson et al. 1965), mesoescale system growth through mergers and downdraft invigoration (Simpson et al. 1980), the use of floating target to provide a more sensitive measurement of the effects of seeding and the finding that the radar-estimate were accurate enough to make inference about seeding effect (Woodley et al. 1982). The EXPAREX design was addressed as continuity of above related experiment, thus it is based on the results of Cuban experiments conducted in CMS during 1985-1990 (Koloskov et al. 1996) and similar to the design of the Thailand cold-cloud seeding experiment (Silverman et al. 1994; Woodley et al. 1999). Consequently, the dynamic-seeding conceptual model as discussed by Rosenfeld and Woodley (1993) was adopted, including secondary seeding concept (Woodley and Rosenfeld, 2002).
According to the conceptual model, the glaciogenic seeding produces rapid glaciations in the updraft by freezing, preferentially the largest drops so that they can rime the rest of the cloud water into graupel. This seeding-induced graupel grows faster than rain drops of the same mass (Sednev et al. 1996), so that a large fraction as the cloud water is converted into precipitation before being lost due to other processes (Rosenfeld and Woodley, 1996). These processes results in increased precipitation and a stronger downdraft, increasing rainfall in the cloud cluster through downdraft interaction between groups of seeded and non-seeded clouds, increases their growths and mergers. Secondary seeding (Woodley and Rosenfeld, 2002) whereby non-seeded clouds ingest ice embryos from earlier seeding of separate clouds, have an important role in the propagation of seeding effect.

4. DYNAMICAL SEEDING-PROPER CLOUD CHARACTERISTICS

Over Cuba persistent Eastern winds blow from the Atlantic Ocean through all troposphere, so that the air mass in which CMS cumulus clouds are rising is basically maritime. According to that, this clouds may be good candidates to early freezing of the rain drops and ice multiplication (Woodley et al. 1993; Mossop 1976) and not suitable for dynamical seeding. In order to investigate the phase composition (Pérez et al. 1994), data from 58 clouds were used, penetrated at the level of 5600-6000 m (-7 to -10 °C in most of cases). All cumulus selected were experimental clouds which tops heights range between 6000-8000 m at the time of penetration. Only not-seeded clouds, or the first pass of seeded clouds, were included in the data set. To study the behaviour of the phase composition, the freezing coefficient K was defined as:

\[
K = \frac{\text{IWC}}{\text{IWC} + \text{LWC}} \times 100
\]

The coefficient K represents the fraction of frozen water and may be used to describe its evolution. IWC and LWC as measured with Nevzorov probe are given for particles with \( r < 120 \, \mu m \). Ice particle concentration (N with \( r > 120 \, \mu m \)) was measured using Mee-120.

In Figure 1, the time evolution of solid phase, can be studied using simultaneous measurements of radar and aircraft. Cloud lifetime was defined as the time elapsed from first echo to dissipation. In order to describe the stage of cloud development at the time of penetration, a time scale was defined as \( t/t_0 \) were t is the time elapsed from the first echo to penetration and \( t_0 \) is the cloud lifetime.

As can be appreciated, both parameters increase with the time, but in the first third of clouds lifetime N (2-6 \( \ell^{-1} \)) and K (10-20 %) are small enough and begin to increase in the second third but not dramatically. We can see that in the first third of cloud lifetime the LWC budget is greater enough with respect to IWC and the onset of ice is not so rapid and no early glaciation of supercooled water is observed. Thus, the phase composition allows the alteration of clouds dynamic according to dynamic mode seeding conceptual model.

In the Table 1 we show natural and potential buoyancy enhancement (B and BE), calculated for a small sample of
15 updraft as defined by Czys (1991) as region of clouds with vertical velocities greater than 1 ms\(^{-1}\) for at least 3 continuous seconds of flight.

To determine the buoyancy it was used the equation:

\[
B = (\theta_v - \theta'_v) - L_{lwc} - L_{iw} \tag{2}
\]

Where \(\theta_v\) and \(\theta'_v\) are the virtual potential temperature of cloud and environment respectively (Czys, 1991), \(L_{lwc}\) and \(L_{iw}\) are the net loading of liquid water contents and ice water contents. The warming due to instantaneous isobaric freezing was obtained with the equation found in Orville and Hubbard (1973).

\[
\delta T = T' - T = \frac{L_f}{c_p}Q_l + \frac{L_s}{c_p}[q_w(T) - q_i(T')] \tag{3}
\]

Where \(T'\) and \(T\) are the parcel temperature after and before glaciation, \(L_f\) and \(L_s\) the latent heat of fusion and sublimation, \(Q_l\) the liquid water expressed as kg of water per kg of air, \(q_w\) and \(q_i\) are the saturation mixing ratio with respect to water and ice.

As can be seen, when instantaneous isobaric freezing is simulated, more than 60% of the cases with negative buoyancy, become positively buoyant. The isobaric freezing warming \(\delta T\) averaged 0.64 °C and ranged from 0.47 to 0.85 °C.

Table 1. Buoyancy enhancement.

<table>
<thead>
<tr>
<th>Diam (m)</th>
<th>LWC (g/m(^3))</th>
<th>B (°C)</th>
<th>BE (°C)</th>
<th>(\delta T_f) (°C)</th>
<th>(\delta T_d) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>0.413</td>
<td>-0.429</td>
<td>-0.284</td>
<td>0.221</td>
<td>0.315</td>
</tr>
<tr>
<td>500</td>
<td>0.145</td>
<td>-0.253</td>
<td>0.374</td>
<td>0.078</td>
<td>0.394</td>
</tr>
<tr>
<td>400</td>
<td>0.291</td>
<td>-0.437</td>
<td>0.255</td>
<td>0.156</td>
<td>0.368</td>
</tr>
<tr>
<td>400</td>
<td>0.030</td>
<td>-0.292</td>
<td>0.314</td>
<td>0.016</td>
<td>0.441</td>
</tr>
<tr>
<td>1500</td>
<td>1.533</td>
<td>-1.421</td>
<td>-0.301</td>
<td>0.833</td>
<td>0.015</td>
</tr>
<tr>
<td>1200</td>
<td>1.278</td>
<td>-1.057</td>
<td>-0.213</td>
<td>0.685</td>
<td>0.099</td>
</tr>
<tr>
<td>1500</td>
<td>1.567</td>
<td>-1.662</td>
<td>-0.546</td>
<td>0.836</td>
<td>0.009</td>
</tr>
<tr>
<td>700</td>
<td>0.784</td>
<td>-0.332</td>
<td>0.574</td>
<td>0.419</td>
<td>0.269</td>
</tr>
<tr>
<td>500</td>
<td>0.673</td>
<td>0.483</td>
<td>1.403</td>
<td>0.360</td>
<td>0.341</td>
</tr>
<tr>
<td>1700</td>
<td>0.356</td>
<td>0.985</td>
<td>1.779</td>
<td>0.190</td>
<td>0.413</td>
</tr>
<tr>
<td>1600</td>
<td>0.683</td>
<td>-0.750</td>
<td>0.564</td>
<td>0.367</td>
<td>0.246</td>
</tr>
<tr>
<td>1100</td>
<td>0.204</td>
<td>-0.439</td>
<td>0.232</td>
<td>0.110</td>
<td>0.396</td>
</tr>
<tr>
<td>1400</td>
<td>0.989</td>
<td>-0.728</td>
<td>0.205</td>
<td>0.533</td>
<td>0.171</td>
</tr>
<tr>
<td>800</td>
<td>0.331</td>
<td>0.123</td>
<td>0.865</td>
<td>0.177</td>
<td>0.386</td>
</tr>
<tr>
<td>1800</td>
<td>0.713</td>
<td>0.024</td>
<td>0.895</td>
<td>0.381</td>
<td>0.280</td>
</tr>
</tbody>
</table>

Diam - Diameter of updraft; B – Buoyancy; BE – Buoyancy enhancement; \(\delta T_f\) – Warming due to freezing; \(\delta T_d\) – Warming due to depositional processes.

Therefore, though the sample presented herein is small, the response given for updrafts to the simulated instantaneous isobaric freezing, reinforces the physical possibilities of alteration of cloud dynamics by glaciogenic seeding.

On the other hand, maritime clouds with lower cloud droplet concentration and wider drop sizes distributions have active coalescence processes, producing glaciation at -10 °C or warmer. These clouds are not proper for glaciogenic seeding mode.

As illustration of the microstructure characteristics of CMS clouds, Figure 2 shows the droplet spectra for the measurements made in 12 cumulus clouds located over the Caribbean Sea (curve 2) and 5 located over CMS (curve 1). Maritime clouds were at a distance which ranged from 140 to 240 km offshore to the south (Pérez et al. 1992).

Figure 2 shows also averaged size spectra as obtained by Hindman et al. (1992), in continental (curve 4) and maritime clouds (curve 5). The mean value for the concentration drops inside the clouds over Camagüey was 380 cm\(^{-3}\) and the mean droplet radius was 6.1 µm. At the same time, over the Caribbean Sea, the mean value of droplet concentration was 64 cm\(^{-3}\) and mean radius of 15.2 µm.
As can be appreciated, clouds developing over CMS can be considered as intermediate and closer to continental.

Clouds are suitable for an effective dynamic seeding when they have a proper coalescence process satisfying the presence of some rain and drizzle drops interspersed in high cloud water contents (Woodley and Rosenfeld, 2003).

Using radar information and airborne measurements made with a photoelectric spectrometer ($D>200 \mu m$) of cloud particles, from 139 penetration of not seeded cumulus clouds in their lower part and with tops between 3.7 and 11.4 km (Beleaev et al. 1994).

The behaviour of spectral rainfall intensities as calculated from the measured particle size distribution is shown in the Figure 3, where it is possible to appreciate that in the warm clouds having less than 5 km tops, with only coalescence mechanisms participating in rain formation, a unimodal distribution of precipitation intensities can be observed. For these cases, curve 1 (clusters) and 2 (isolated) are showing an active coalescence process, with peak at 2.5 mm raindrops diameter and some larger than 4mm. Two modes in the distributions were observed in clouds whose tops were above the freezing level.

In such cases, both mechanisms, warm and cold, were likely to operate (Petrov et al. 2004).

In Figure 4 we show the frequency histogram for updrafts and downdrafts from measurements made at the levels of 5.6 – 6.1 km in the periods 1987-1990 and 2006-2007.

In the updraft cases, the most part ($\approx 85\%$) ranged up 2 to 17 m$^{-1}$ and some cases above 18 m$^{-1}$ ($\approx 10\%$) for both periods. In 1987-1990 cases $\approx 64\%$ of the updraft are between 4 -16 m$^{-1}$ and 74% for 2006-2007. Updrafts over passing 6 m$^{-1}$ are 56% and 57% in the first and second periods respectively. In considering downdrafts for both periods practically all
case are grouped between 0 and -12 ms\(^{-1}\) (≈ 97%).

As we can see, in both periods experimental cloud properties meet the necessary criteria of strong updraft for dynamic seeding.

In the Figure 5 we can observe the same, because of the enough high quantities of clouds water at the seeding level.

According to the behaviour of the phase composition, without glaciated up to -10 °C or warmer levels and considering the values of LWC and vertical velocities in updraft, we can express that the cold convective clouds developing in CMS are suitable for the application of the conceptual model of dynamical seeding.

Nevertheless, in the absence of particle measurement probe in Cuban experiments, it is not possible to obtain directly, spectral characteristics of solid and liquid phase at seeding level. However considering the behaviour of clouds characteristics given in the Figures 3 and 4 for both periods, is possible to considerer that we are working with similar process in similar clouds. These condition allows the comparison between the measurements of ice particles (D>200 µm) made with the Mee-120 in the 1986-1990 period and measurements of cloud particles (solid and liquid) made with a photoelectric spectrometer for large (D>200 µm) cloud particles in the period 2006-2007. The comparison showed the presence of raindrops at the level of seeding, with concentration ranged between 0 to 11 ℓ\(^{-1}\) and an exception with concentration up 21 ℓ\(^{-1}\). The values of concentration obtained are comparable with measurements in South Africa (Mather et al, 1986) and Illinois (Czys and Scott, 1993).

Average for maximum values for 1986 -1990 was 1.025 gm\(^{-3}\) and for 2006 – 2007 it was 1.12 gm\(^{-3}\). In the first period, 85% of LWC values are above 0.4 gm\(^{-3}\) and in the second the 87%.

The behaviour of frequency distribution for mean values of LWC in both periods result practically the same. Average for 1987 -1990 was 0.486 gm\(^{-3}\) and for 2006 – 2007 0.488 gm\(^{-3}\).

The comparison made with two different devices, in order to obtain raindrop concentration at the seeding level, may be inexact and should be use carefully. The future use of a laser beam particle measuring system, wich allows to discern the phase of the particles, is essential to accurately asses the presence of supercooled raindrop.

5. CONCLUSIONS

The design of EXPAREX experiment was based in results from the experiments in Cuba (1985-1990), West Texas 1987-1990, Thailand 1987-1990 and facets of FACE-I and FACE-II. The EXPAREX design
was addressed as continuity of above related experiments period, and is similar to the design of the Thailand cold-cloud seeding experiment. As conceptual model guiding, the dynamic-seeding, the revised conceptual model as developed and discussed by Rosenfeld and Woodley (1993) was adopted.

The following arguments show that the towers of cold convective cumulus clouds developing over CMS satisfy the conceptual model for dynamic-seeding:

- The behaviour of the freezing coefficient and ice crystal concentration showed that, the LWC was greater than IWC and the crystal concentration was small enough, providing suitable conditions for seeding with glaciogenic reagents. The time evolution showed that in the first third of cloud lifetime the development of solid phase is slow and it increases in the second third but not dramatically, allowing a seeding window for the CMS clouds.

- The results of simulation of isobaric freezing in some updrafts, suggest that most of negatively buoyant ones would have become nearly neutral, or positively buoyant if they had been seeded. This reinforce the possibilities of alteration of cloud dynamic by glaciogenic seeding.

- In the analysis of droplet spectra measurements made over ground and sea, in the same day an during two consecutive days with the same synoptic conditions, it was found that spectra obtained for clouds over land are radically different from those for offshore clouds. That allows to conclude that clouds growing over CMS are nearly continental by their microstructural properties.

- The form of the raindrop size distributions obtained for the lower part of the clouds show an active coalescence process, showing, peaks at nearly 2.5 mm in raindrop diameter and the presence of some drops larger than 4mm for warm clouds having tops less than 5 km, for which the ice processes had no participation in rain formation.

Data of LWC, ice crystal concentration, vertical in clouds air motions and the suggestion of the presence of raindrops at the seeding level, provide a consistent picture of cloud structure in the supercooled region which indicate that is possible a proper application of glaciogenic seeding, within the vigorous supercooled updraft with enough high LWC and some raindrops interspersed, generated from below by coalescence. That is according with the dynamic-seeding revised conceptual model as adopted by the design of EXPAREX.

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7. REFERENCES


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